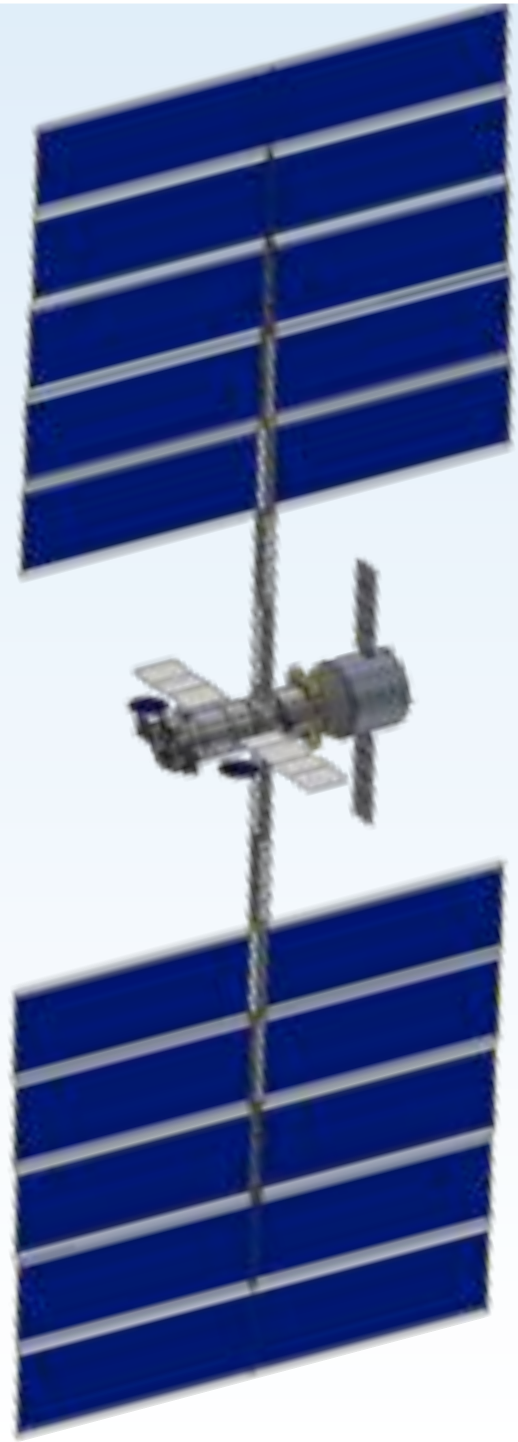
Piloted Mars Combined SEP-Chem.:

Conjunction Piloted and Cargo Designs



COMPASS Team
NASA John H. Glenn Research Center
Steven.R.Oleson@nasa.gov

12-14-12

Steve Oleson
FISO Telecon 3-6-2013

COMPASS Team

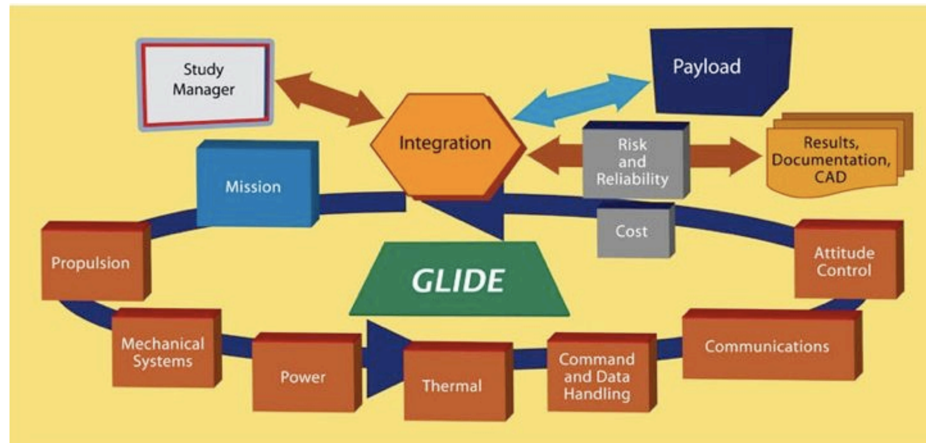
- Project Customers: Bret Drake, Carolyn Mercer, Tim Smith
- Lead - Steve Oleson
- System Integration, MEL - Melissa Mcguire
- Mission Visualization – Michael Martini
- Operations, PEL – David Grantier
- Mission –Laura Burke
- ACS - Mike Martini
- Propulsion - James Fittje, Dan Herman
- Mechanical Systems - John Gyekenyesi
- Environmental- Tony Colozza
- Power – Kristen Bury, James Fincannon
- C&DH, Software - Glenn Williams
- Communications - Joe Warner
- Configuration - Tom Packard
- Cost - Jon Drexler
- Risk - Anita Tenteris

COMPASS Concurrent Engineering Team

(*COllaborative Modeling for Parametric Assessment of Space Systems)*

The COMPASS team is a multidisciplinary concurrent engineering team whose **primary purpose is to** perform **integrated vehicle systems analysis** and provide **conceptual designs and trades** for both Exploration and Space Science Missions.

Design Process



Data Transfer Process

Subsystem models integrated via a vehicle Master Equipment List worksheet

Team formally established in 2006, Mission Driven

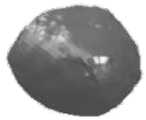
COMPASS products tailored to support proposals, project reviews per NPR 7123.1A (especially MCRs & SRRs) and implementation of technologies

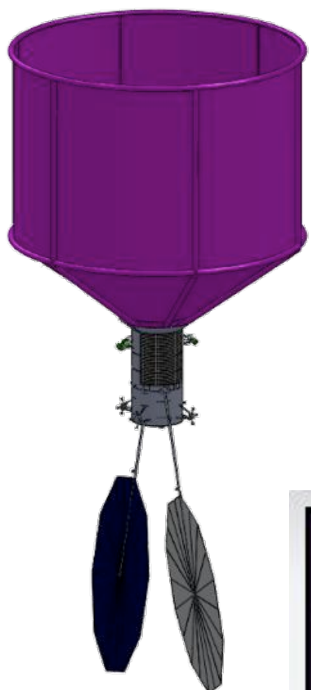
COMPASS works very closely with other NASA flight centers, Gov't Organizations, Industry, and Projects

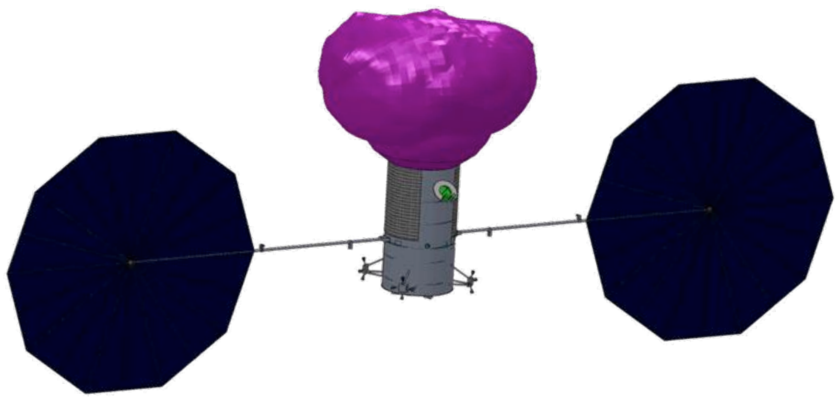
The concurrent engineering process produces solid engineering designs quickly without the rework needed by isolated teams

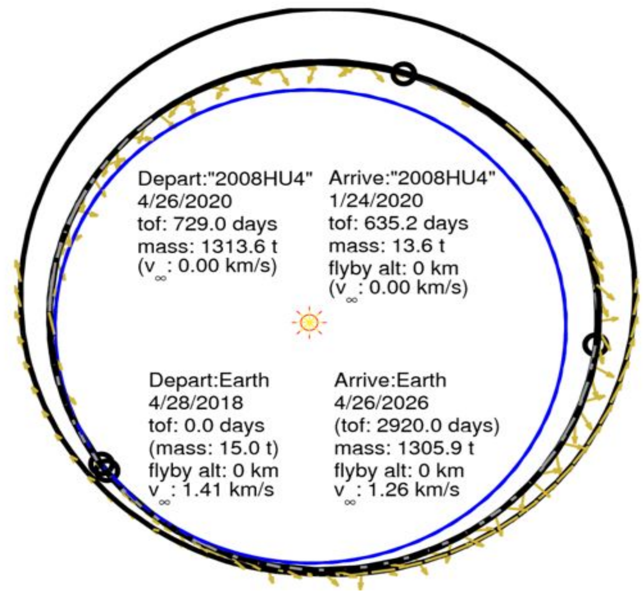
Over 90 designs to date!!!

COMPASS Asteroid Return Design Makes ‘Mainstream’





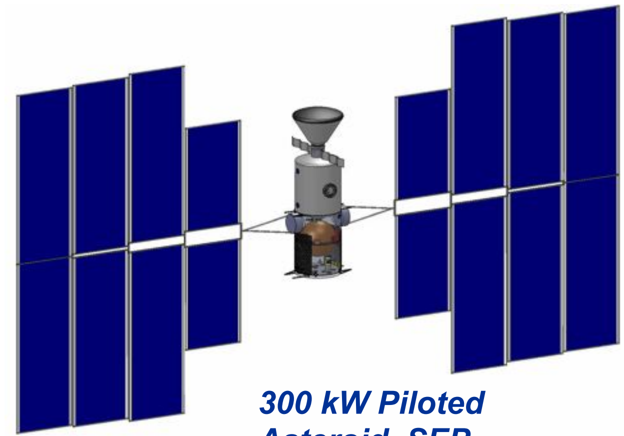




Design Performed for the Keck Institute

Recent Piloted Related Designs

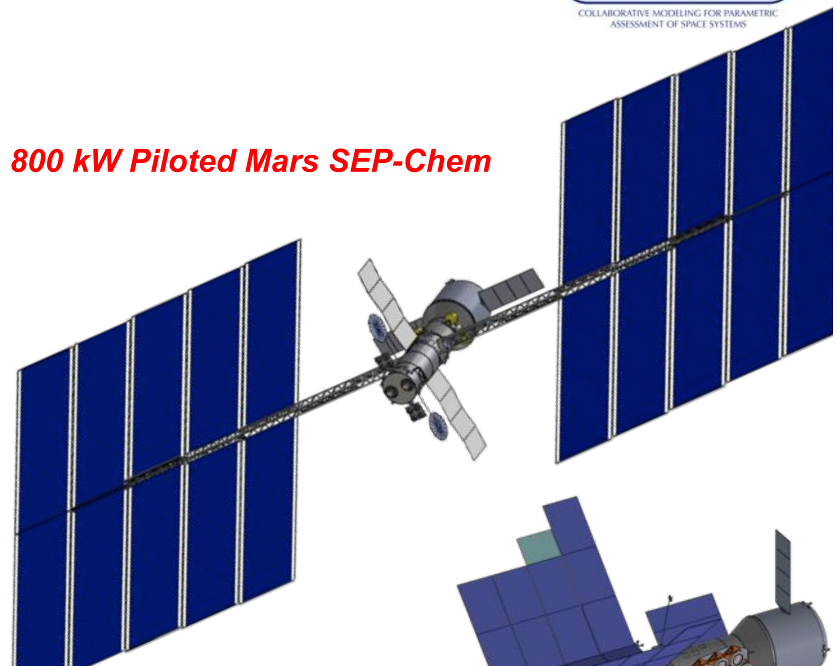
COMPASS



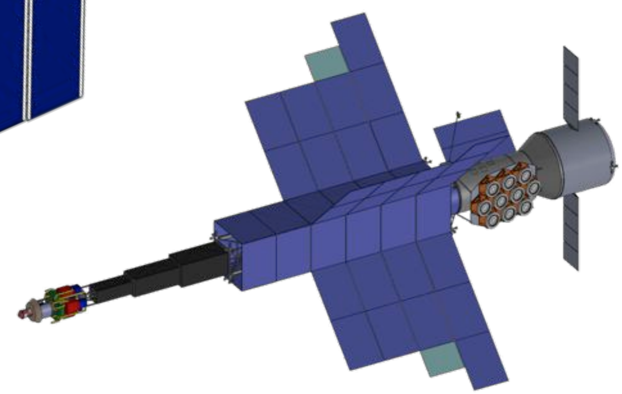
300 kW Piloted Asteroid SEP

L2 Waypoint Habitat

Piloted Gateway Vehicle

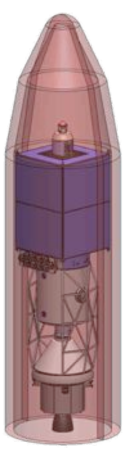


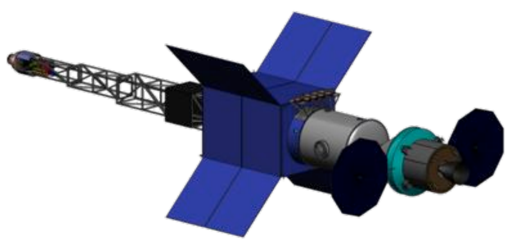
800 kW Piloted Mars SEP-Chem



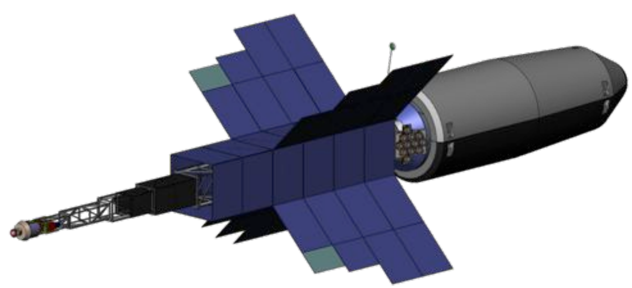
2.5 MW Piloted Mars NEP

Piloted Asteroid Vehicles For the NASA Enabling Technology and Development Team





300 kW Piloted Asteroid NEP



1 MW Cargo Mars NEP

Piloted Mars Vehicles for the Human Spaceflight Architecture Team

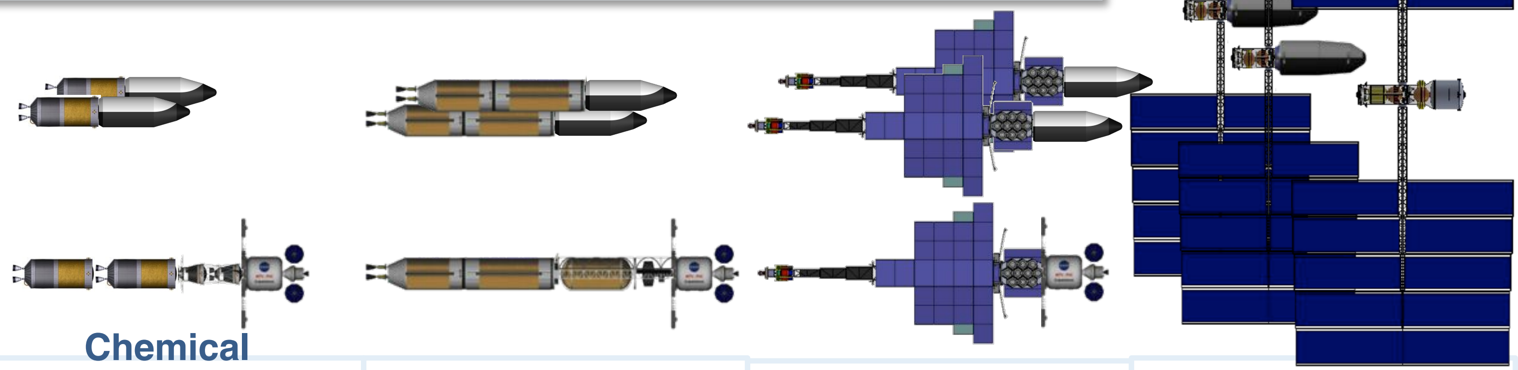
Purpose

- Build upon previous COMPASS Electric Propulsion assessments to develop High power SEP-Chem. crew vehicle concepts supporting human exploration of Mars
- Scope: Assess one crew vehicle mission concepts:
  - Conjunction class – 2037 harder opportunity across the synodic cycle
    - Show impact of staying less than 500 days – (400 days used for the SEP)
  - Drive out a higher fidelity concepts taking into consideration other aspects such as
- FOMs: # of SLS launches, Mars stay time, interplanetary time, Mass, TRL
- More detailed operational concept
  - Configurations
  - Launch packaging
- Drive out key technologies and sensitivities
  - Power level
  - Alpha
- Products
  - Design Reference Mission overview, CONOPS, spacecraft concept, MEL, PEL, risks
    - Start with Conjunction Vehicle, Modify for Opposition
- Schedule – Mon (week of T-giving), MWF following week 1:30-4:30pm eastern

National Aeronautics and Space Administration

Launch Campaign and Transportation Options

Number of SLS launches and spacing between launches driven predominately by the mission mode and transportation architecture



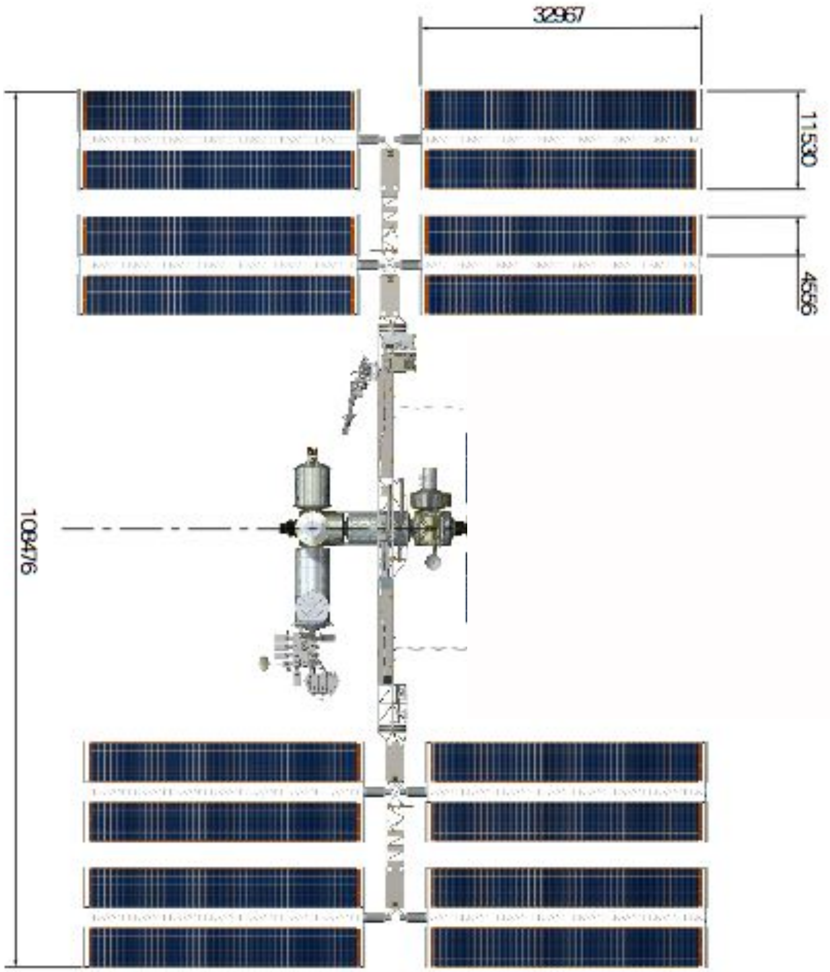
	Chemical Propulsion		Nuclear Thermal		Nuclear Electric		Solar/Chem	
Parameter	**“Hard” Long-Stay (500d)**	**“Easy” Short-Stay**	**“Hard” Long-Stay (500d)**	**“Easy” Short-Stay**	**“Hard” Long-Stay (400d)**	**“Easy” Short-Stay**	**“Hard” Long-Stay (300d)**	**“Easy” Short-Stay**
Total Mass (t)	~1,200	~1,450	~600	~700	~550	~700	~490t	n/a
# SLS Launches	~12	~13+	~9	~9+	~7	~9+	~7	n/a
SLS Delivery to LEO (t)	105 & 130	105 & 130	105	105	105 & 130	105 & 130	105 & 130**	n/a
SLS Shroud Dia./ Barrel	10 / 22	10/22	10/25	10/29	10/25	10/25	10/10	n/a
Launch Spacing (days)*	50-100	45-90+	70-120	70-120+	90-150	70-120+	90-150	n/a

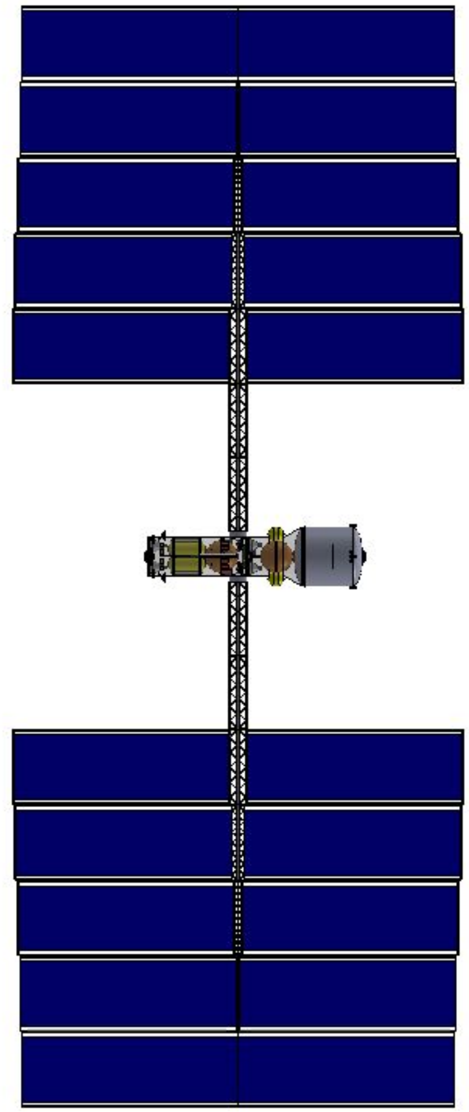
“Hard” Long Stay Represents most stressing conjunction class (2037 long-stay) mission. Typical mission values will be less for other opportunities.
“Easy” Short-Stay Represents the easiest opposition class (2033 short-say) mission. Values for other opportunities will vary greatly and will be much more stressing.
Launch Spacing* Lower/upper values represent spacing required for crew missions every opportunity (26 months) and every-other opportunity (52 months) respectively.
**Depending upon SLS performance 1-2 ATV launches using a Ariane 5 class vehicle are required to provide consumables

Assumptions from Previous Chart

- Chemical
  - Used MSFC presentation to HAT:
    - "HAT Mars Chem Propulsion Arch Study 2012-04-26.ppt", Mass totals from pages 73 & 74.
    - Instead of EELV propellant launches, assumed equivalent propellant on SLS @ 110 t of propellant each launch
- NTP
  - Used MSFC and GRC presentations to HAT
    - "2012-06-07_HAT_TechIntForum__NTR_GRC.pdf", page 8
    - "2012-06-07_HAT_deliverable_LK_v2.ppt", page 4
    - Assumed 2 cargo landers at 103 t each
    - Assumed 1 core and ½ in-line tank required for each cargo lander
- NEP
  - Used GRC presentation to HAT
    - "2012-07-26_Piloted_NEP_Final_Draft_v7.pptx", pages 5 & 6
    - Assumed 2 cargo landers at 103 t each
    - Assumed 1MWe NEP (113 t each) required for each cargo lander as on page 7
- SEP-Chem.
  - Used GRC presentation to HAT

Relative Sizes





Rough High Thrust Piloted Mission Options (for comparison)

# SLS launches	**20**		Storable	**7**		Cryo	**9**		Cryo/ Storable	**3**		NTR
SLS launch mass	114	ΔV	Isp	114	ΔV	Isp	114	ΔV	Isp	114	ΔV	Isp
IMLEO	2280			798			1026			342		
mass at Earth departure	663	4000	330	322	4000	450	415	4000	450	217	4000	900
Departure Stage	404			119			153			31		
Mass after dropped stage	258			204			262			186		
mass after Mars capture	196	900	330	166	900	450	198	900	330	168	900	900
Capture Stage	16			9			16			5		
Mass after dropped stage	180			157			182			164		
mass after Mars Departure	113	1500	330	112	1500	450	115	1500	330	138	1500	900
Departure Stage	17			11			17			6		
Mass at Earth Flyby	97			100			98			132		
Gear Ratio (kg drop & prop/kg inert returned)	**22.6**			**7.0**			**9.5**			**1.6**		

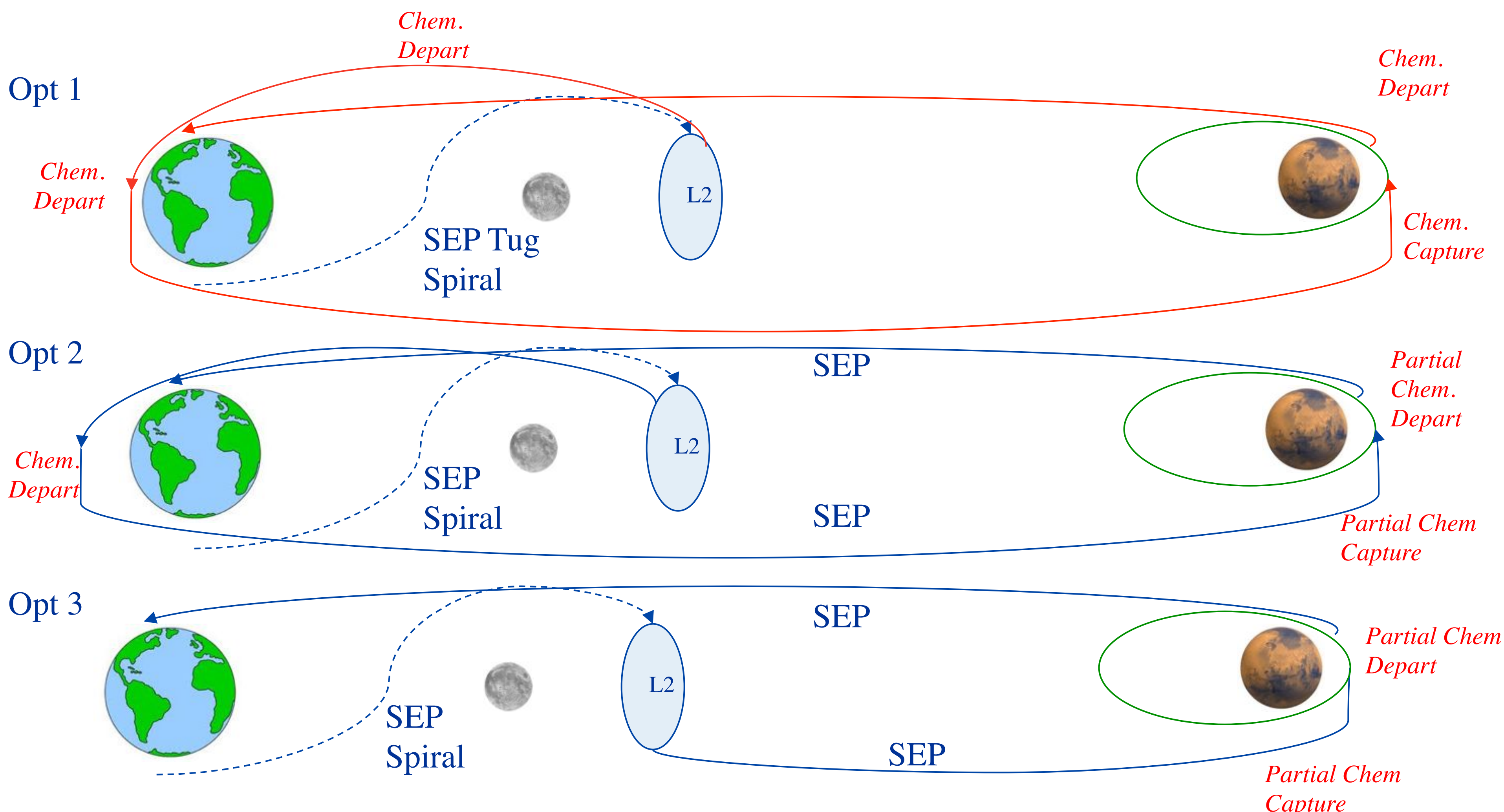
- Impulsive ΔV ~ 6400 m/s! – with impulsive Isps staging is a must!
- Lion's Share of ΔV is Earth Departure (~4000 m/s) – Cryo stage needed for at least this phase
- NTR baseline for DRA 5.0 – best impulsive Isp – fewer SLS launches

SEP Scaling Options
(based on initial ΔV estimates)

# SLS launches	3	Opt 1	SEP/ Stor.	3	Opt 2	SEP/ Stor.	2	Opt 3	SEP/ Stor.	2	Opt 4	SEP/ Stor.	2	Opt 5	SEP/ Stor.
SLS launch mass (less insertion prop, margin 5%, adapter)	108	ΔV	Isp	108	ΔV	Isp	108	ΔV	Isp	108	ΔV	Isp	108	ΔV	Isp
IMLEO	324			324			216			216			216		
mass at Gateway (rendz w MPCV)	224	6480	2000	257	6480	2000	190	6480	2500	186	6480	2300	186	6480	2300
xenon propellant	67			67			26			30			30		
xenon Tanks	7			7			3			3			3		
mass after Earth Flyby	157	1150	330	180	1150	330	190	0	355	186	0	355	186	0	355
chem propellant	67			77			0			0			0		
Chem tanks	7			8			0			0			0		
mass before Mars capture	157	0	2000	163	2000	2000	163	3729	2500	137	6000	2000	137	6000	2000
xenon propellant	0			17			27			49			49		
xenon Tanks	0			1			1			2			2		
mass after Mars capture	119	900	330	144	400	330	147	364	355	137	0	355	137	0	355
chem propellant	38			19			16			0			0		
Chem tanks	4			2			2			0			0		
mass after Mars Departure	75	1500	330	127	400	330	134	319	355	137	0	355	137	0	355
chem propellant	44			17			13			0			0		
Chem tanks	4			2			1			0			0		
mass before Earth Arrival	75	0	2000	115	2000	2000	121	2566	2500	115	4000	2300	115	4000	2300
xenon propellant	0			12			13			22			22		
xenon Tanks	0			1			1			1			1		
Inert Mass	75			102			107			93			93		
Gear Ratio (kg drop & prop/kg inert returned)	**3.3**			**2.2**			**1.0**			**1.3**			**1.3**		

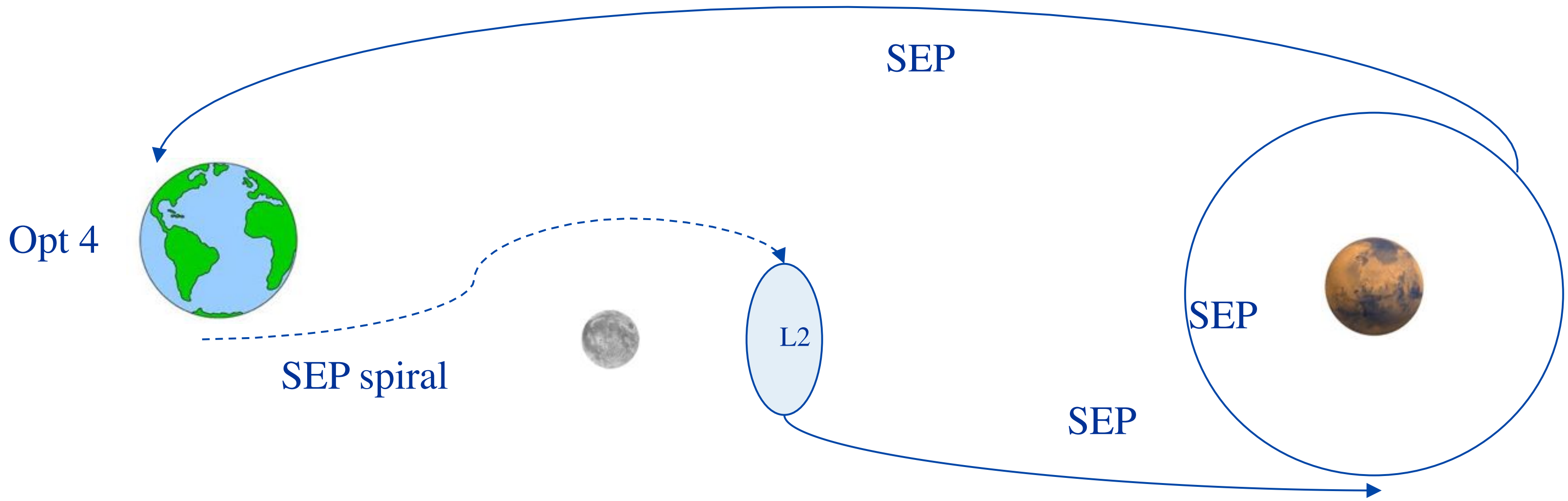
- Unmanned SEP spiral replaces large chemical departure – (ΔV increase from ~4000 m/s to ~6500 m/s BUT Isp ~4X larger than Cryochem and saves multiple SLS launches of propellant)
- Option 1 – just using SEP ‘Tug’ to remove large departure stage major impact
- But can a large SEP system be used to Mars and Back?
- We found it can (~ 1 MW and 2 SLS) but at the cost Mars stay time (reduced to ~50 days for conjunction)
- We also found that sharing the Mars capture between SEP and Storable Chem increases stay times back to 300 days – NO staging required!

SEP Options



- Options to use SEP
- Crew meets up with vehicle at L2
- Option 3 found to be the best mix of stay time, Required IMLEO, and simplicity

All SEP Option



- Crew meets vehicle at L2
- SEP spiral down to 24 hr circular Mars orbit

Mission Options
(Grayed out options yet to be massed out)

Option	LEO to EML2	Earth/ Moon Depart Flyby	Interplanet Propulsion	Mars Gravity Well Propulsion	Mars Parking Orbit	Launch Req'ts	Mars Stay Time	Notes
1.1 'SEP-Tug'	SEP	Chem	None -Coast	Chem	Elliptic 1 Sol	4 SLS?	500d?	SEP 'tug' option, SEP vehicle does not fly to/from Mars
2.1	SEP	Chem/ SEP	SEP	Chem	Elliptic 1 Sol	2 SLS, 3 ATV class tankers		
3.1 'Baseline SEP-Chem.'	SEP	None – SEP from gateway	SEP	Chem	Elliptic 1 Sol	2 SLS, 2 ATV carrying 15t	300 d	ATV tankers bring up biprops and crew consumables – adds 3 months to stay time
4.1 'All-SEP'	SEP	None – SEP from gateway	SEP	SEP	Circular 1 Sol	2 SLS, 2+ ATV carrying 18t	45d	Replaced chemical tanks with an additional xenon tank on SEP stage
5.1	SEP	Chem/ SEP	SEP	SEP	Circular 1 Sol			
6.1	SEP Cargo	None – SEP from gateway	SEP	None – Cargo does its own aerocapture	None – SEP flys by Mars	2 SLS (1 SEP , 1 Aeroshell cargo	NA	Chemical tanks replaced on SEP with a second Xenon tank, 300V, 2870s Isp, PPUs

- 1-5 options use 800 kW EOL/1AU, 500V power systems with 2400 sec Direct Drive Nested Hall thrusters. Chemical burns performed with Orion-Derivative Storable systems

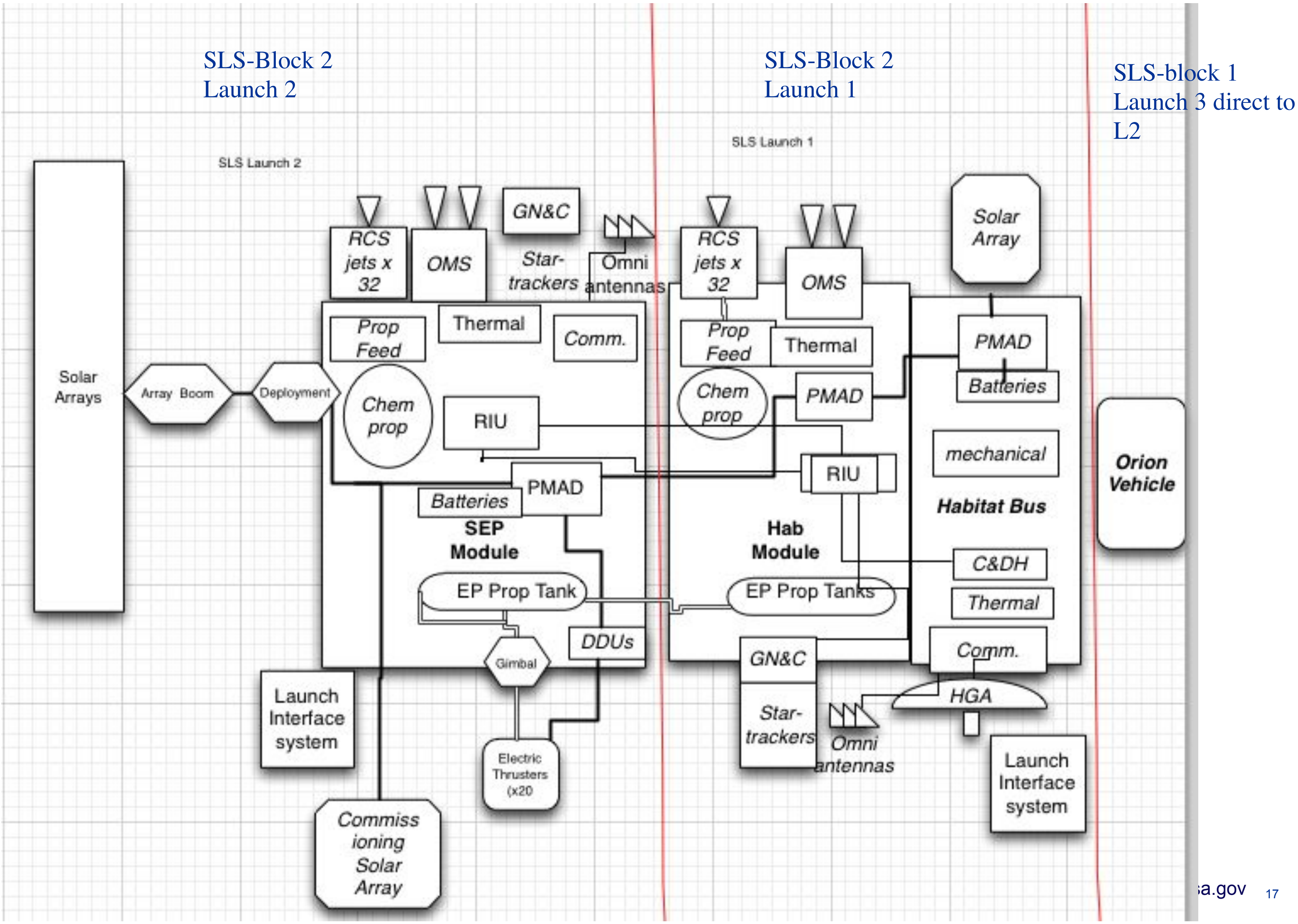
Technology Trades

Option	Power (EOL/ 1AU)	Propulsion (EP /Chem)	Launch Req'ts	Mars Stay Time	Notes
3.1 (Configuration Designed)	800kW, 500V	2400 s Direct Drive Nested Hall / 327 s storable	2 SLS, 2 ATV carrying ~15t	300 d	ATV tankers bring up biprops and crew consumables – adds 3 months to stay time
3.2	800kW 300V	2000 s Isp Nested Hall (12 @ 75 kW)	2 SLS, 6 ATV class cargo	300 d	Power System Change (heavier solar array and PMAD), DDUs the same, More propellant, larger tanks
3.3	800 kW, 500V	349 s LOX/LCH4	2 SLS, 2+ ATV carrying ~18t	270d	Requires active cooling of cryo propellants, transfer of cryo propellants needed, lower propellant density, foam insulation, longer structures more than offsets the benefit of higher Isp
3.4	800 kW, 500V	2400 s Isp, NASA-457 Hall thrusters (20 @ 50kW)	2 SLS, 2 ATV carrying ~15t	300 d	Higher TRL thruster (50kW @ 2400s) assume same eff and DDU as Nested at 2400s. Heavier system (20 thrusters, larger platform (2.2x3.75m), more lines)
3.5	800kW, 300V	3000 s/ 2140 s PPU Nested Hall (12 @ 75 kW) / 327 s storable	2 SLS, 2 ATV carrying ~12t	300 d	Not direct Drive, added PPU mass, larger radiators (PPU ~97%). Unpiloted spiral 3000s, piloted 2140 or 3000s LEO to Gateway spiral time up to 630 days (from 480d) due to 3000 sec

TRL Options

- Propulsion:
  - EP: 50 kW Thruster [5], 200 kW Thruster(80 kW demonstrated) [4], xenon [9], krypton [5-6], Direct Drive (10 kW 'array on roof') [3-4], Supercritical storage [9], Large supercritical tanks [4-5]
  - Chemical: MMH/NTO Orion derivative [7-9], LOX/LCH4 thruster [4-5], LOX/LCH4 ZBO storage [4-5]
- Power: Direct drive [3-4], High voltage arrays (300-600V) [3], lightweight IMM Cells (33%) [5], Advanced stowage and deployment systems [3], High voltage Electronics [4-5], Battery [5]

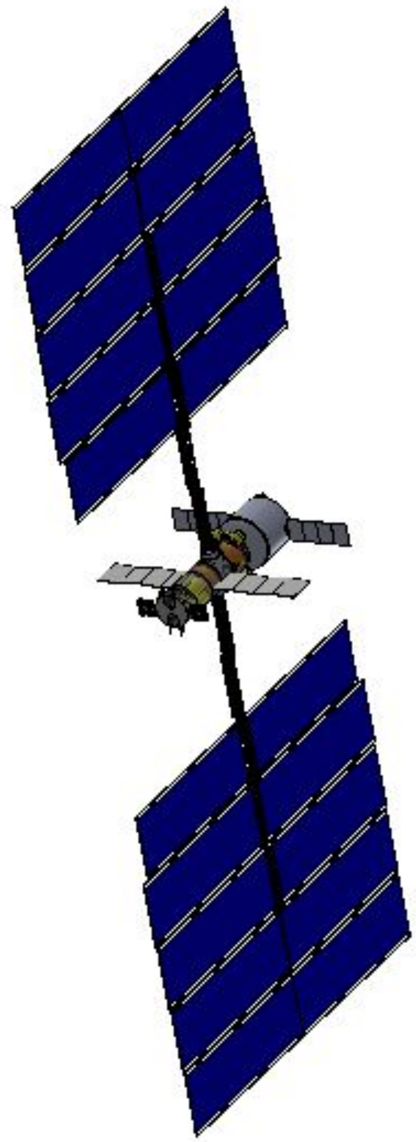
System Schematic



Just a little over an SLS….

- If one is 1-10t over an SLS launch what are the options (besides a whole other SLS launch)?
- Chemical propellant (~40 t)
  - Storable chemical bipropellants have been transferred on orbit for many years
- Xenon propellant (~100t)
  - High pressure might make this difficult
- Hab Module consumables
  - Up to 15t of supplies
  - Would require a piloted commissioning flight to unload
  - Perhaps the water could be pumped.

Mission:
Laura Burke and Mike Martini



COMPASS Team
NASA John H. Glenn Research Center

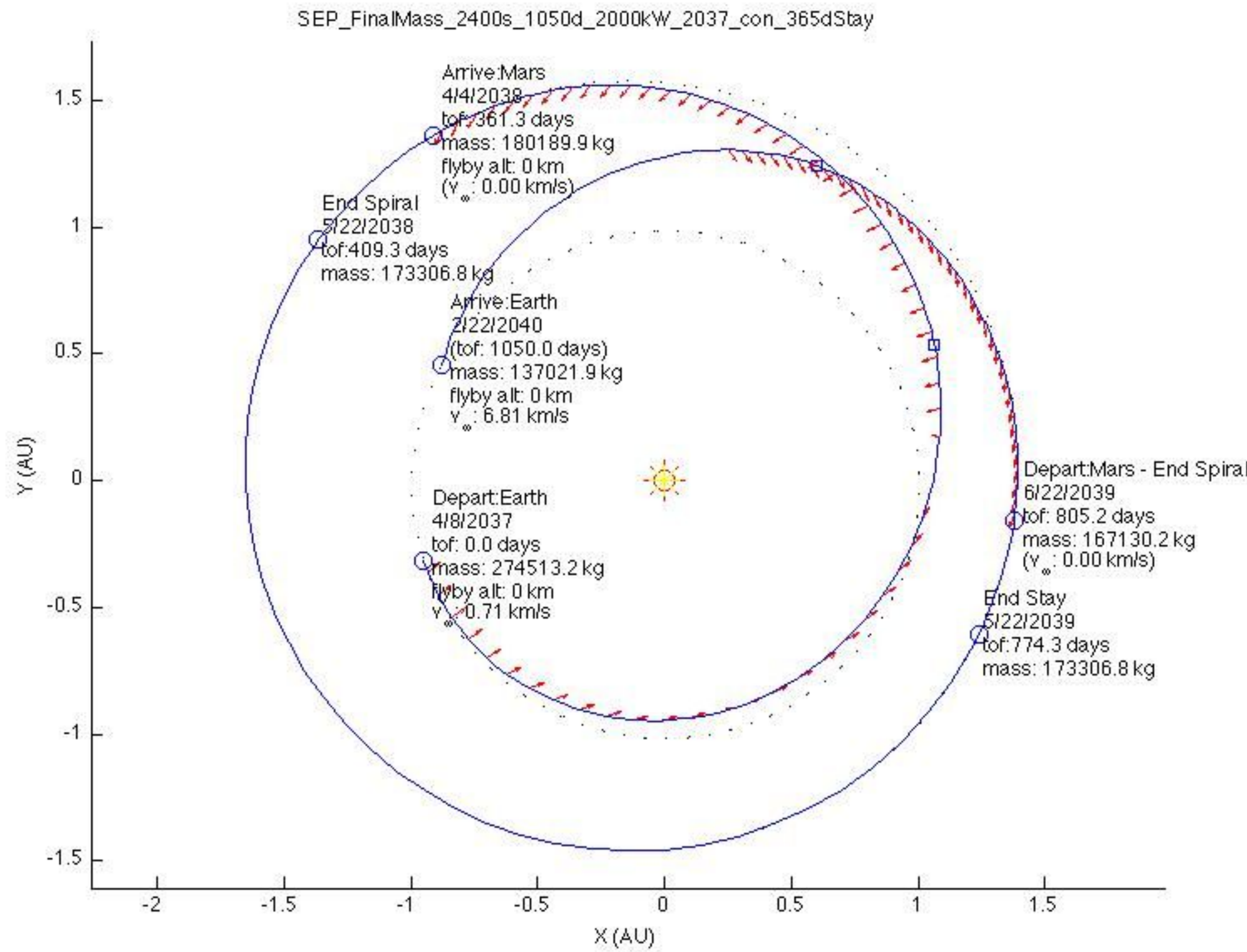
12-14-12

All SEP Trajectory Trades

All SEP Option Assumptions

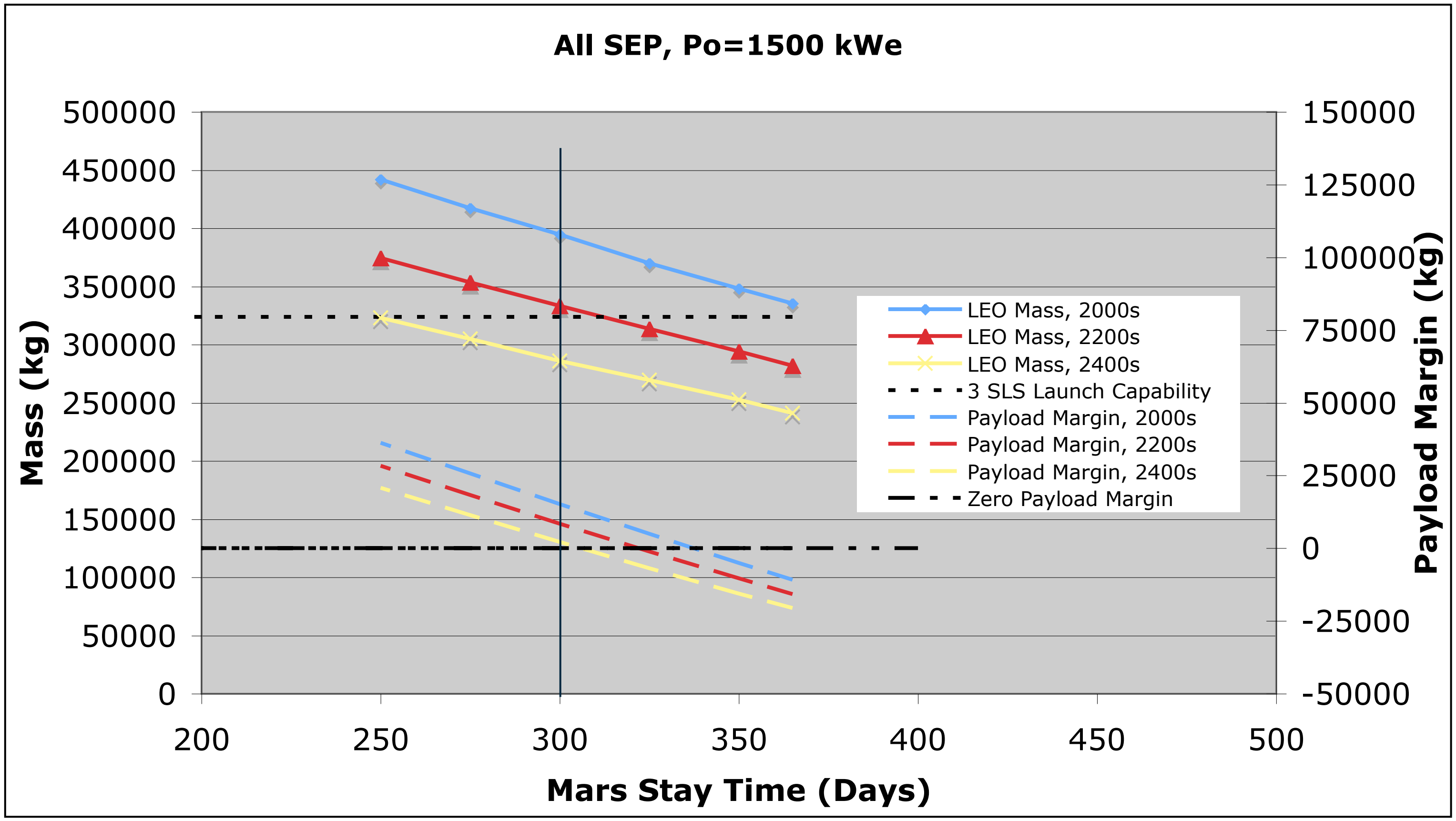
- 2037 Opportunity, conjunction class mission
- Mass assumptions
  - Inert mass assumptions at the beginning of the study
    - MPCV = 24 Mt
    - Hab = 53 Mt
    - Tank Mass is 4% of propellant mass
    - Power system alpha = 20 kg/kWe
    - Structure Mass is 27% of (Tank Mass + Power System Mass)
  - After the study started, the inert mass of each element from the COMPASS design was used along with the 24 Mt MPCV
- Use same power level and Isp as the SEP-Chem. mission
  - Power = 800 kWe
  - Isp = 2400 s
- SLS Launch capability of 113.8 Mt to a -92.6 km x 407 km orbit
- Each element inserts itself into 407 km circular orbit
  - 148 m/s of delta-v
  - SEP element Isp for insertion = 327.5 s
  - Hab element Isp for insertion = 316 s due to shorter nozzle
- Spiral from LEO to E-M L2, meet up with crew in the MPCV there, then depart to Mars
- Spiral In/Out of a 24 hr circular Mars orbit (SMA=20,082 km)

All SEP, 2400s Isp, 2000 kWe



- All SEP requires ~ 2MW to provide a 1 year stay time: Spiraling in/ out at Mars takes ~80 days total

300 Day Stay, 1500 kWe



- 2200s gives a 300 day stay with 3.1 SLS launches, 8466 kg of payload margin
- 2400s gives a 300 day stay with 2.6 SLS launches, 2203 kg of payload margin
- Two SLS Launches and lower power are preferred

Combined SEP/Chem Trajectory Trades

Requirements/Objectives/Trades

- Requirements
  - 2037 Conjunction-Class Earth-Mars roundtrip mission using a combined SEP/Chemical trajectory departing from Earth-Moon L2
    - SEP is used for Earth spiral-out and departure and as well as during interplanetary transit
    - Chemical is used for capture and departure into a 24hr elliptical orbit at Mars
- Objectives
  - Total crew time of ~1000 days or less
  - Mars stay time of ~365 days
  - Minimize initial mass of the spacecraft in Low Earth Orbit (LEO) to reduce the required number of SLS launches to 2
- Mission Trades
  - Departure directly from Earth-Moon L2 (EML2) or departure from EML2 to Earth Flyby
    - SEP, Chemical, or SEP+Chemical options
  - Chemical or SEP to capture and depart at Mars
    - Chemical captures into 24 hr elliptical orbit
    - SEP captures into 24 hr circular orbit
  - Isp, Power tradespace
    - Isp: 2000-3000s
    - Power: 600-900 kW

National Aeronautics and Space Administration

Option 2-1 (Chem/SEP Earth Flyby)

(adds two months stay time compared to baseline 3-1 but not completed at time of design study, windows/phasing may be challenging also)

SEP Delta-Vs:

- EML2 Departure: 243 m/s
- Earth Departure: 3309 m/s
- Mars Arrival: 794 m/s
- Mars Departure: 2026 m/s

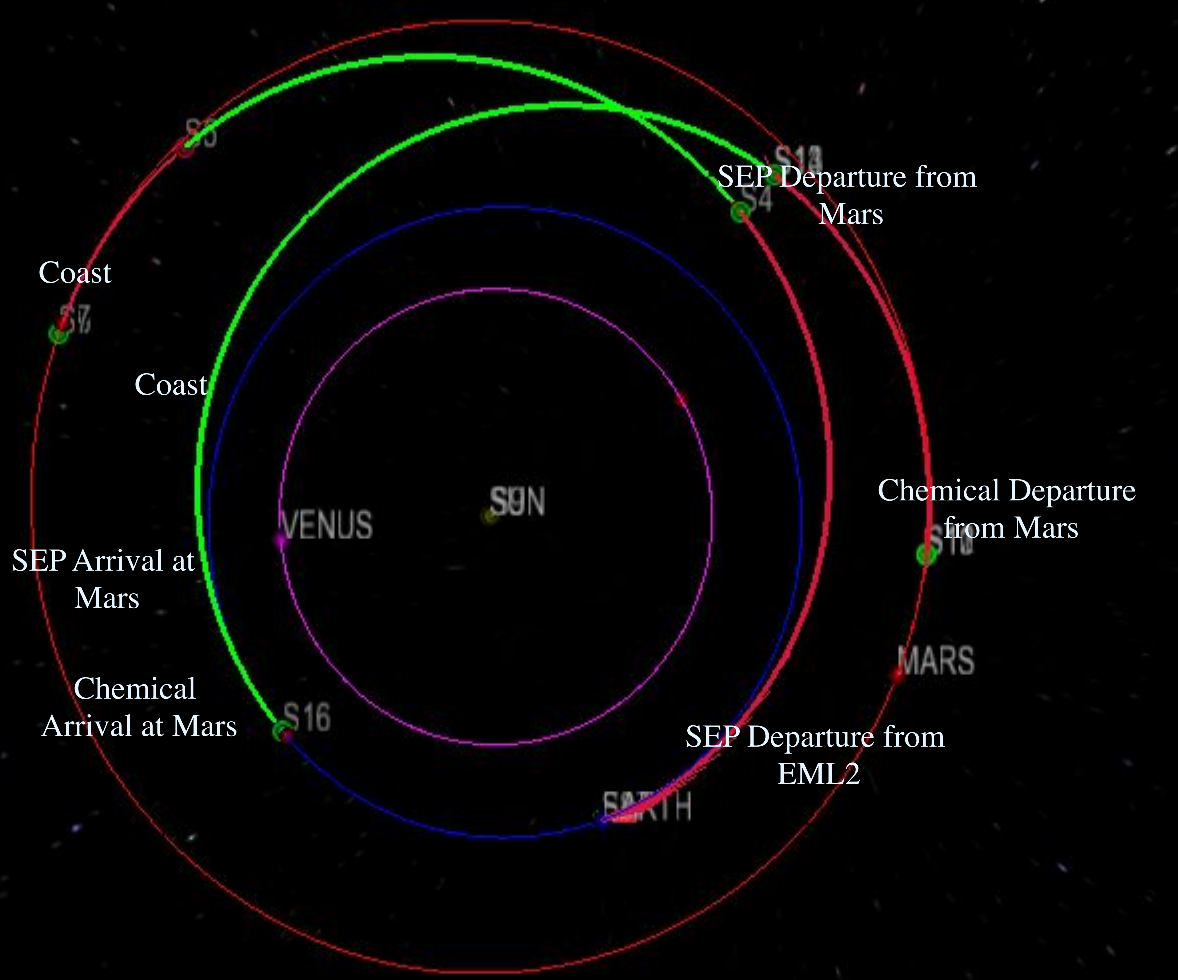
Chemical Delta-Vs:

- Moon Flyby: 233 m/s
- Earth Departure: 68.4 m/s
- Mars Orbit Arrival: 283 m/s
- Mars Orbit Departure: 226 m/s

Earth Flyby Date: July 14, 2037
Mars Arrival Date: June 23, 2038
Mars Departure Date: June 26, 2039
Earth Arrival Date: May 6, 2040

Mars Stay Time: 367 days
Total TOF: 1026 days

Red denotes SEP Thrust periods, Green Coasts

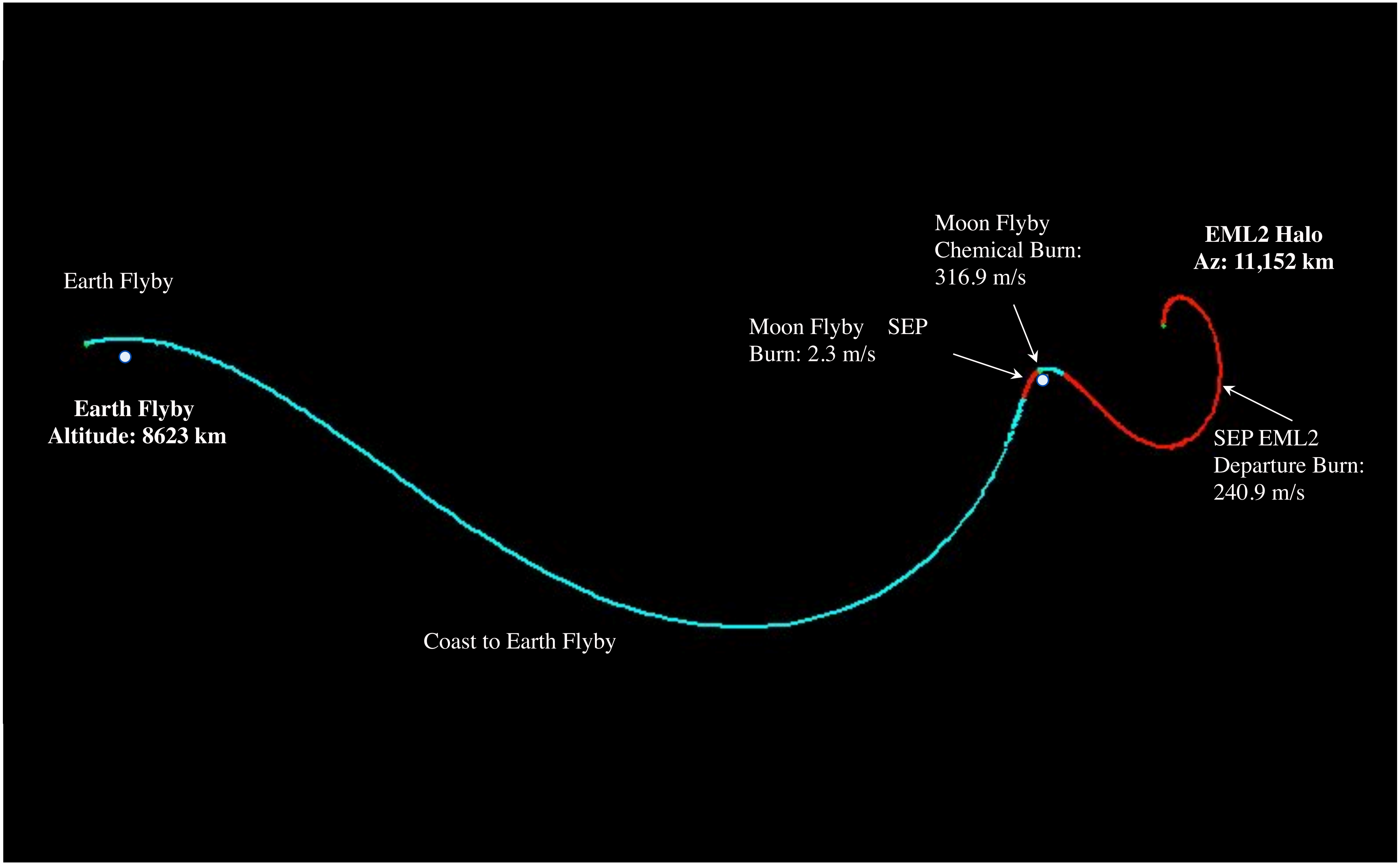


*Assumed inert mass of 125mt

*EML2 to Earth Flyby and Earth-Mars Round trip segments were optimized independently

National Aeronautics and Space Administration

EML2 to Earth Flyby



National Aeronautics and Space Administration

Option 3-1/3-4 (No Earth Flyby, Direct Drive, Baseline)

COMPASS

Red denotes SEP Thrust periods, Green Coasts

SEP Delta-Vs:

EML2 Departure: 4204 m/s

Mars Arrival: 391 m/s

Mars Departure: 2203 m/s

Chemical Delta-Vs:

Mars Arrival: 345 m/s

Mars Departure: 226 m/s

Earth Departure Date: June 17, 2037

Mars Arrival Date: August 30, 2038

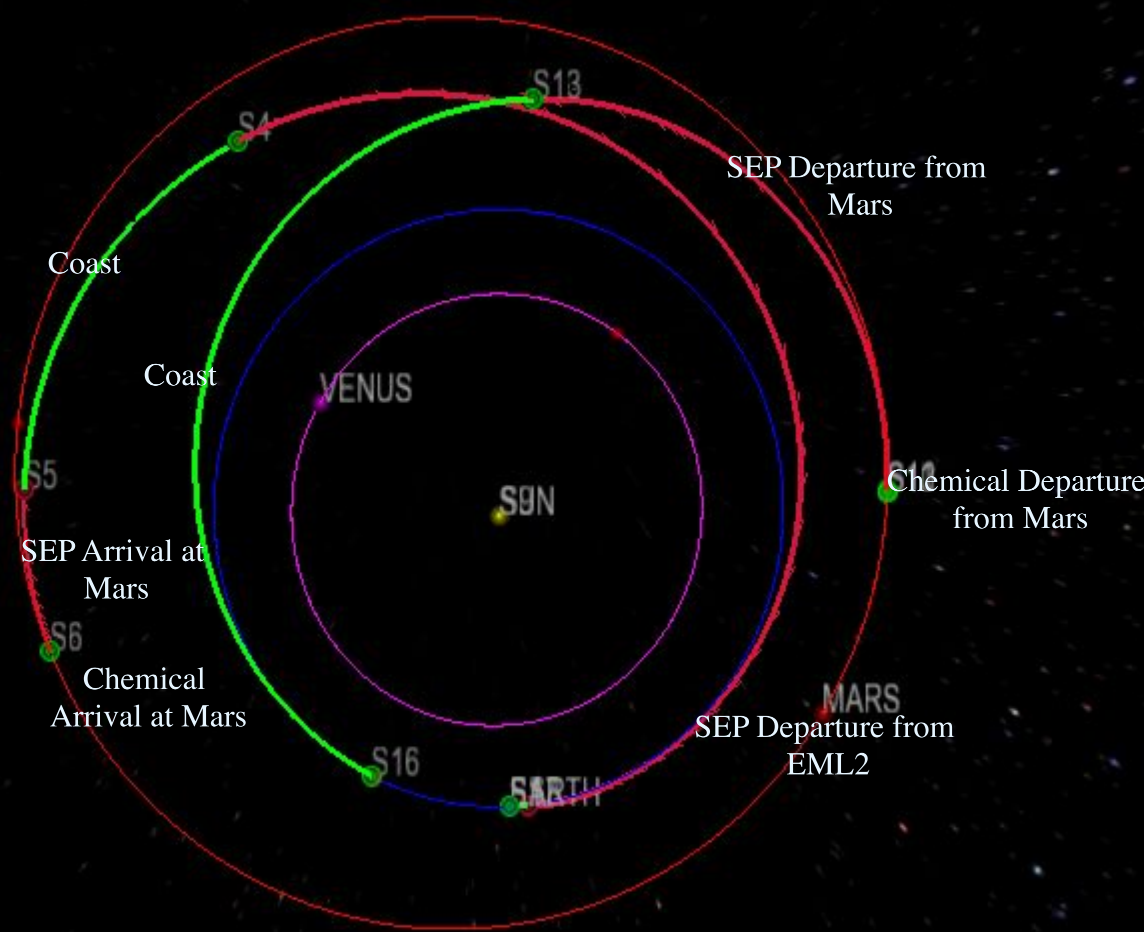
Mars Departure Date: June 26, 2039

Earth Arrival Date: May 17, 2040

Mars Stay Time: 300 days

Total TOF: 1066 days

*Optimized for inert mass of 122mt



Mission Delta-V Summary, Option 3.1

Mission DeltaV Summary								
Phase #	Phase Name	Propellant Utilization	Pre-Burn Mass (kg)	Main DV (m/s)	ACS DV (m/s)	Main Prop (kg)	ACS Prop (kg)	Post Burn Mass (kg)
1	Hab Orbit Boost	Hab Chem	113781	148	0	5306	0	108474
2	Dock Tanker(s) with Hab		108474	0	0	0	0	123045
3	Hab Stationkeeping	Hab Chem	123045	0	10	0	383	122663
4	SEP Element Orbit Boost	SEP Chem	113770	148	0	5124	0	108646
5	AR&D, Hab To SEP Element	Hab Chem	122663	0	5	0	191	231118
6	Attitude Control During Spiral Out	SEP Chem	231118	0	13	0	964	230154
7	Spiral Out To Gateway	SEP EP	230154	2967	0	27256	0	202898
7	Spiral Out To Gateway	Hab EP	202898	3683	0	29394	0	173504
8	Stationkeeping at Gateway	SEP Chem	173504	0	3	0	180	173324
9	MPCV Docks with Hab/SEP Vehicle		173324	0	0	0	0	197144
10	Outbound Heliocentric Leg	SEP EP	197144	2050	0	16447	0	180697
10	Outbound Heliocentric Leg	Hab EP	180697	2546	0	18525	0	162172
11	Attitude Control During Coast	SEP Chem	162172	0	1	0	66	162106
12	Mars Capture Burn	SEP Chem	162106	251	0	12194	0	149912
12	Mars Capture Burn	SEP Chem	149912	94	0	4317	0	145596
13	RCS Burn For Possible Engine Out and CG Offset	SEP Chem	145596	0	9	0	410	145186
14	Stationkeeping	SEP Chem	145186	0	22	0	984	144202
14	Stationkeeping	Hab Chem	144202	0	8	0	366	143836
15	Departure Burn From Mars	SEP Chem	143836	165	0	7183	0	136653
15	Departure Burn From Mars	Hab Chem	136653	61	0	2684	0	133969
16	RCS Burn For Possible Engine Out and CG Offset	SEP Chem	133969	0	6	0	249	133719
17	Inbound Heliocentric Leg	SEP EP	133719	983	0	5469	0	128251
17	Inbound Heliocentric Leg	Hab EP	128251	1220	0	6480	0	121771
18	Attitude Control During Coast	SEP Chem	121771	0	2	0	76	121694

- Some Delta-V's were divided between the two elements to achieve the desired wet mass at launch for each element
  - 33,500 kg of chemical propellant was placed on the SEP element, remaining chemical propellant was then placed on the Hab element
  - EP delta-v split was then adjusted to load the SEP element with xenon such that it had a mass of 113,755 kg on the launch pad
  - Remaining xenon propellant was placed on the Hab element
  - Any amount that the Hab element was over the allowed launch mass by was assumed to be taken up separately in ATV flight(s)
- Many ACS delta-v's were calculated from a required ACS propellant to offset disturbance torques
- Total EP Delta-V = 13.4 km/s, total useable xenon = 103,570 kg
- Total Chem Delta-V = 571 m/s (Mars capture and escape, does not include ACS or LEO insertion burns)

National Aeronautics and Space Administration

Option 3-2 (No Earth Flyby, Non-Direct Drive)

Red denotes SEP Thrust periods, Green Coasts

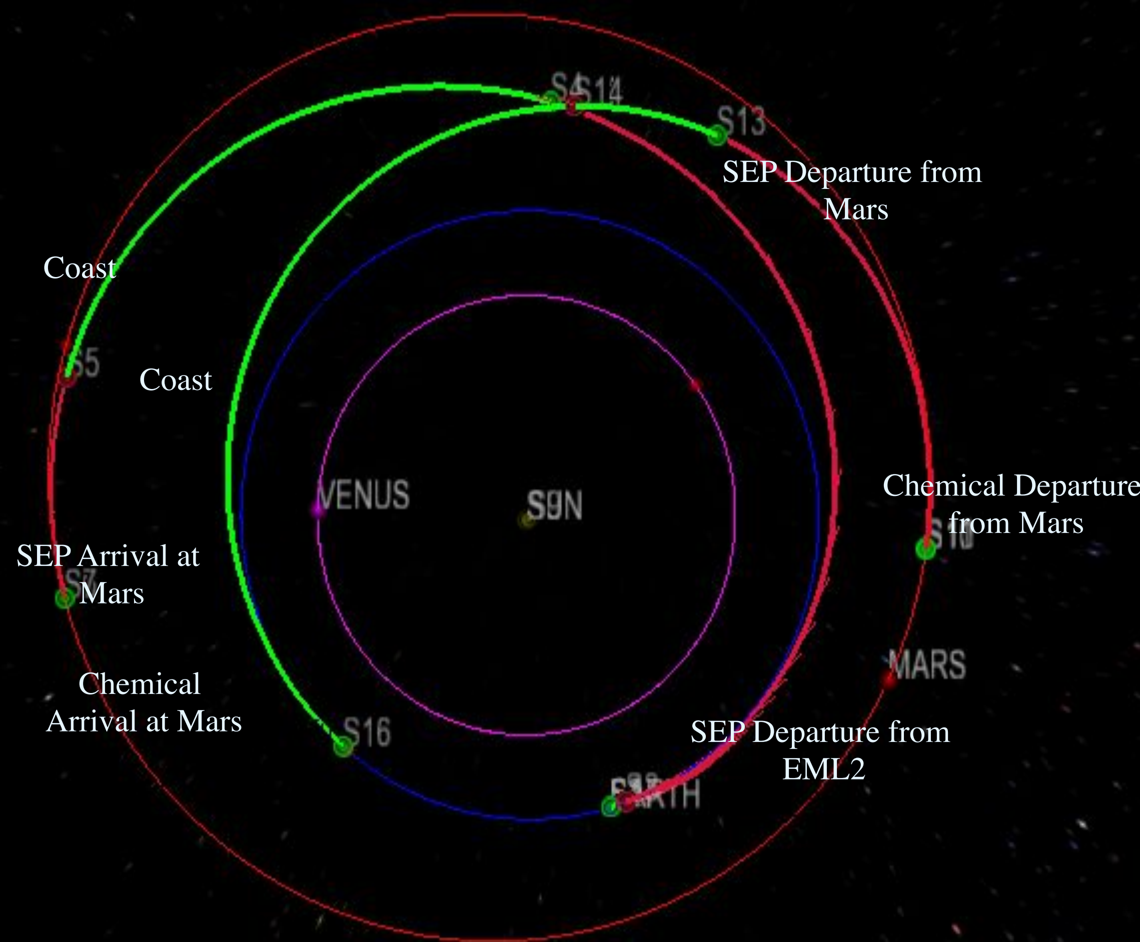
SEP Delta-Vs:
- EML2 Departure: 3614 m/s
- Mars Arrival: 614 m/s
- Mars Departure: 2068 m/s

Chemical Delta-Vs:
- Mars Arrival: 309 m/s
- Mars Departure: 226 m/s

Earth Departure Date: July 8, 2037
Mars Arrival Date: August 28, 2038
Mars Departure Date: June 24, 2039
Earth Arrival Date: May 10, 2040

Mars Stay Time: 300 days
Total TOF: 1037 days

*Optimized for inert mass of 125mt



National Aeronautics and Space Administration

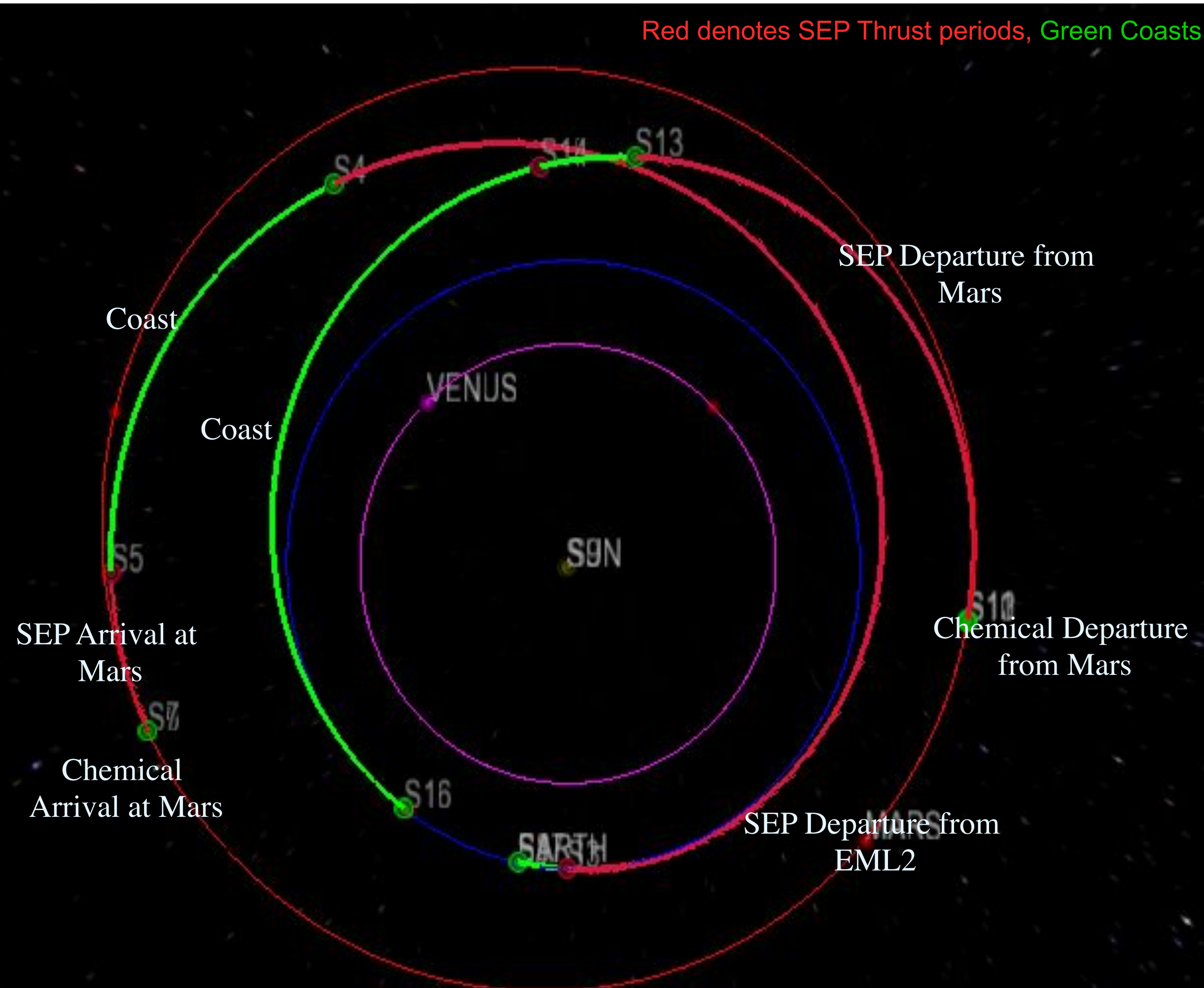
Option 3-3 (LOX/LCH4 Chemical for Mars)

SEP Delta-Vs:
- EML2 Departure: 4063 m/s
- Mars Arrival: 383 m/s
- Mars Departure: 2166 m/s

Chemical Delta-Vs:
- Mars Arrival: 323 m/s
- Mars Departure: 226 m/s

Earth Departure Date: June 10, 2037
Mars Arrival Date: September 23, 2038
Mars Departure Date: June 20, 2039
Earth Arrival Date: May 15, 2040

Mars Stay Time: 270 days
Total TOF: 1070 days



*Optimized for inert mass of 131mt (inert mass above this will require a reduce stay time)

National Aeronautics and Space Administration

Option 3-5 (Non Direct Drive, Two Isp Setpoints)

SEP Delta-Vs:

EML2 Departure: 3650 m/s (2064s)

Mars Arrival: 647 m/s (3000s)

Mars Departure: 2256 m/s (3000s)

Chemical Delta-Vs:

Mars Arrival: 332 m/s

Mars Departure: 226 m/s

Earth Departure Date: July 7, 2037

Mars Arrival Date: August 16, 2038

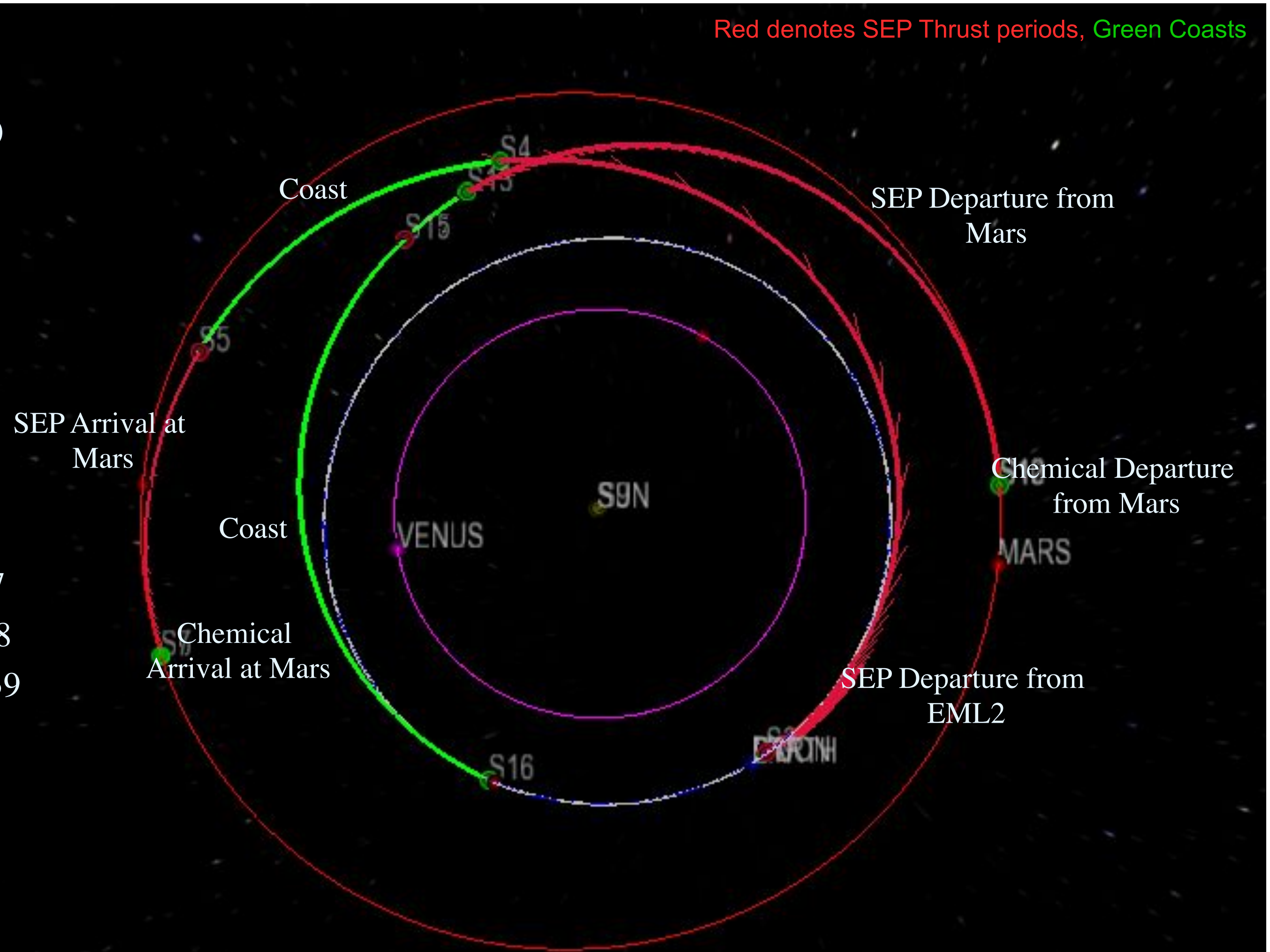
Mars Departure Date: June 12, 2039

Earth Arrival Date: May 14, 2040

Mars Stay Time: 300 days

Total TOF: 1041 days

*Optimized for inert mass of 124mt

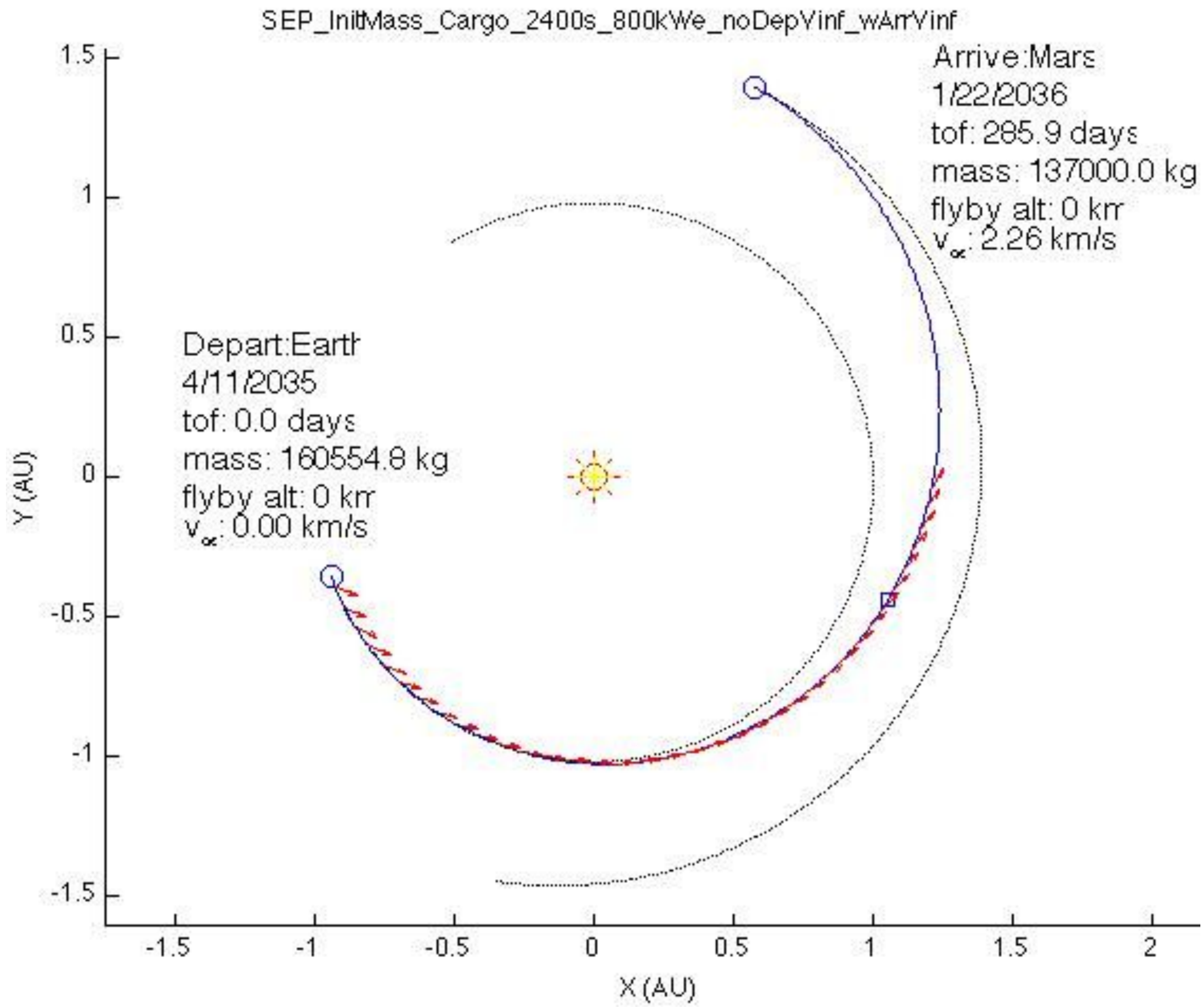


All SEP Cargo Mission

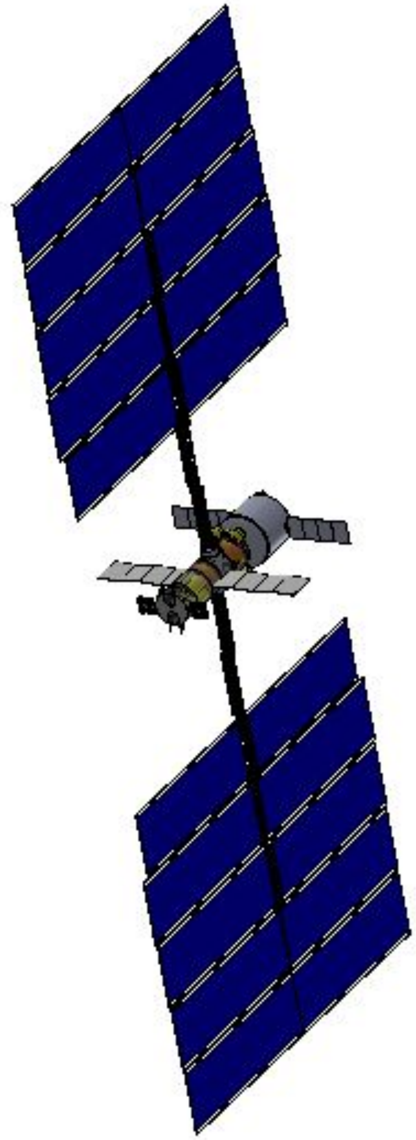
National Aeronautics and Space Administration

Cargo Vehicle – All SEP

- Assumptions
  - Deliver 137 Mt to Mars
    - Cargo vehicle = 103 Mt
    - SEP Vehicle = 34 Mt
  - Delta-v, LEO to escape=7650 m/s
  - Isp=2400s
  - Power=800 kWe EOL at Earth
- Results
  - Minimum mass required in LEO = 222,172 kg
  - Vinf at Mars = 2.26 km/s
  - V at 150 km alt = 5.4 km/s
  - Total Xenon used = 85,172 kg



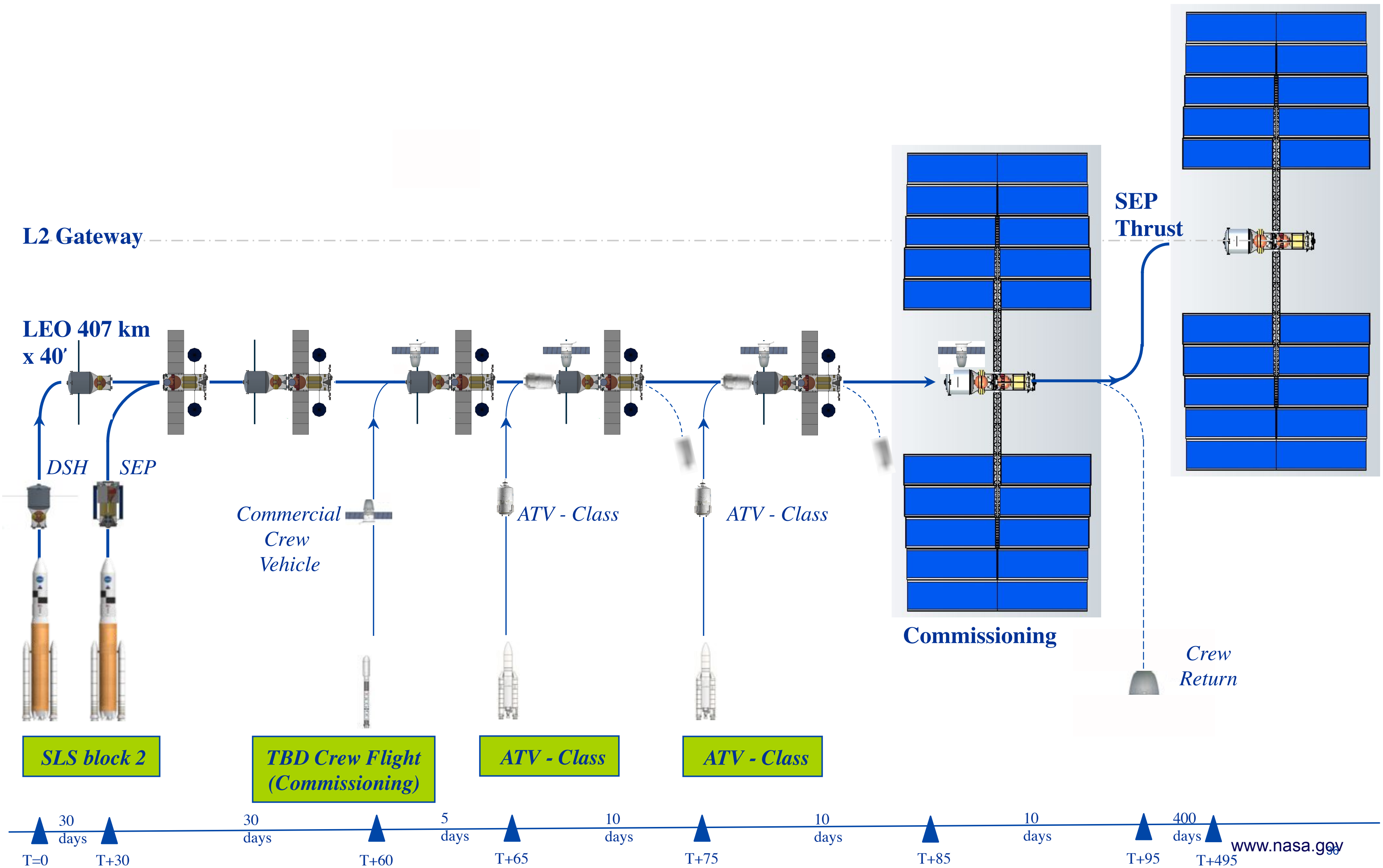
CONOPS and PEL:
David Grantier



COMPASS Team
NASA John H. Glenn Research Center

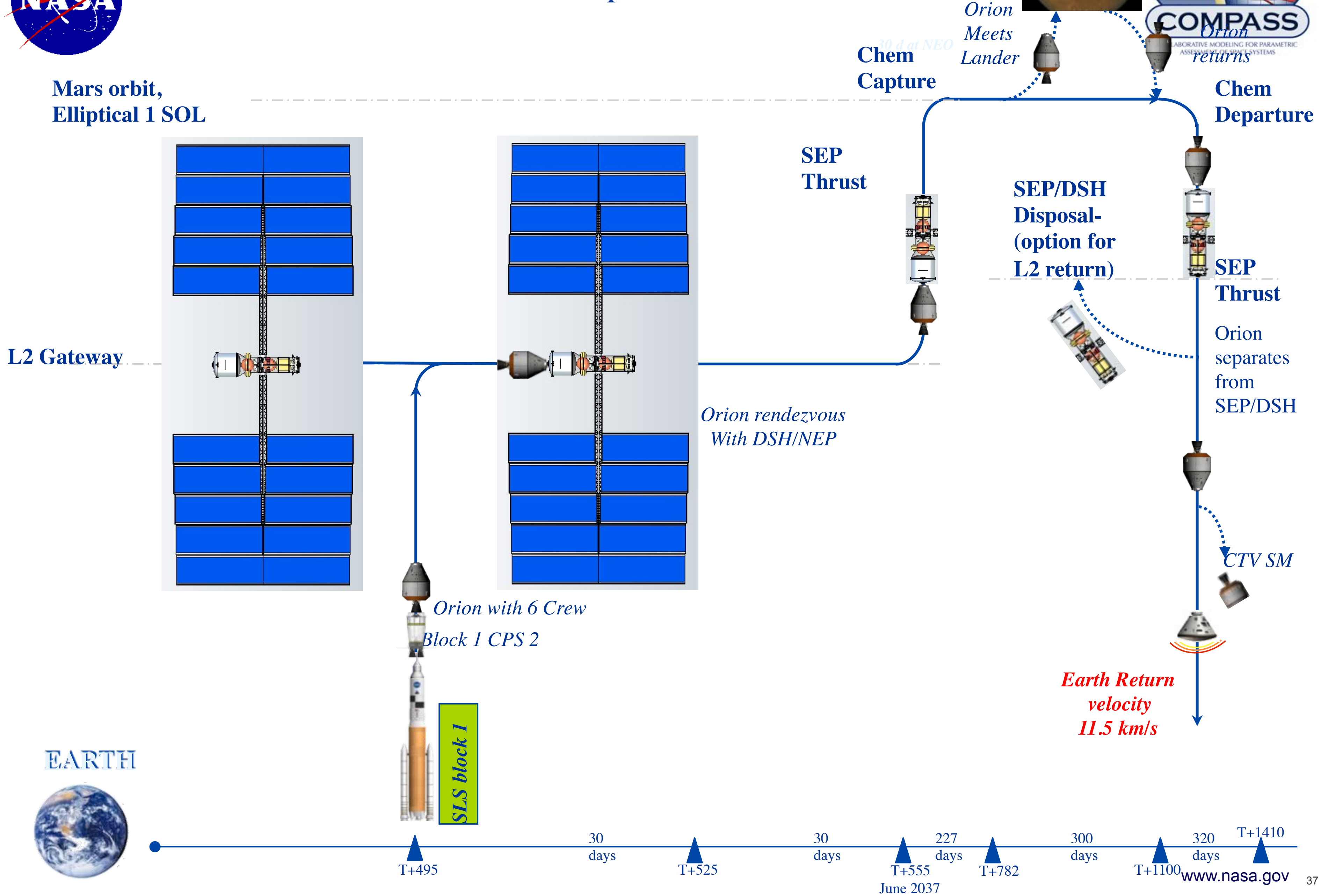
12-14-12

MARS SEP 3.1 ConOps to L2 Gateway



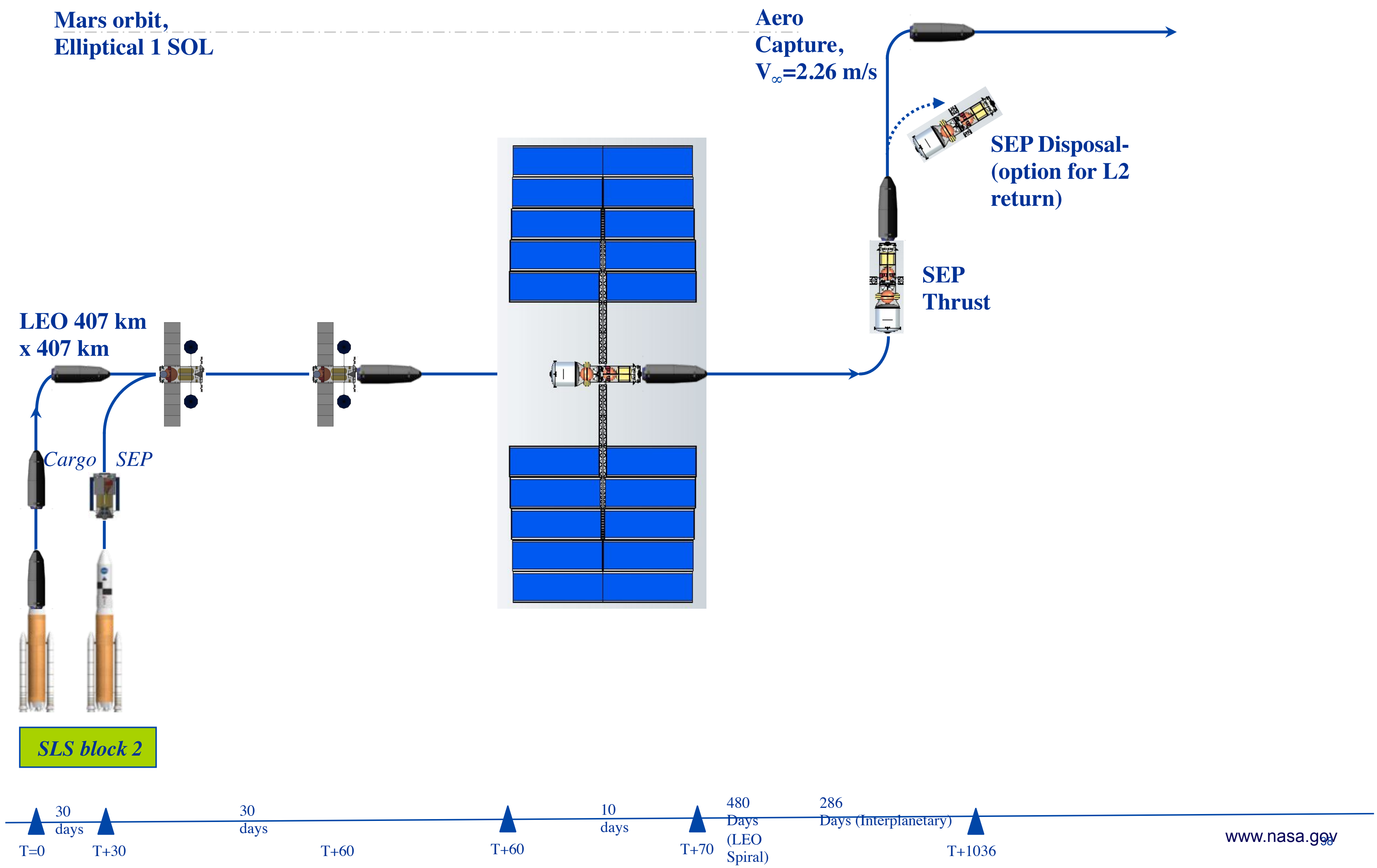
National Aeronautics and Space Administration

Piloted Mars SEP 3.1 ConOps L2 to End of Mission



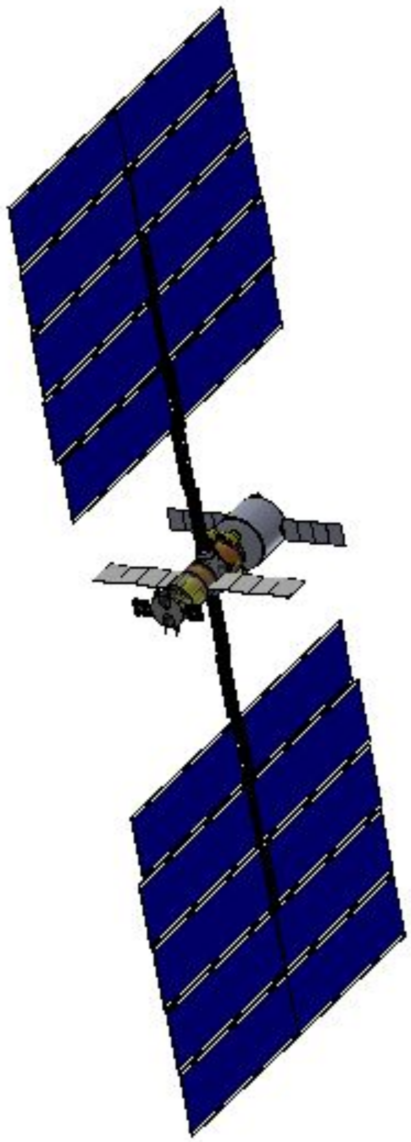
National Aeronautics and Space Administration

MARS SEP 6.1 Cargo ConOps to Mars Elliptical 1 SOL



Configuration:

Thomas Packard

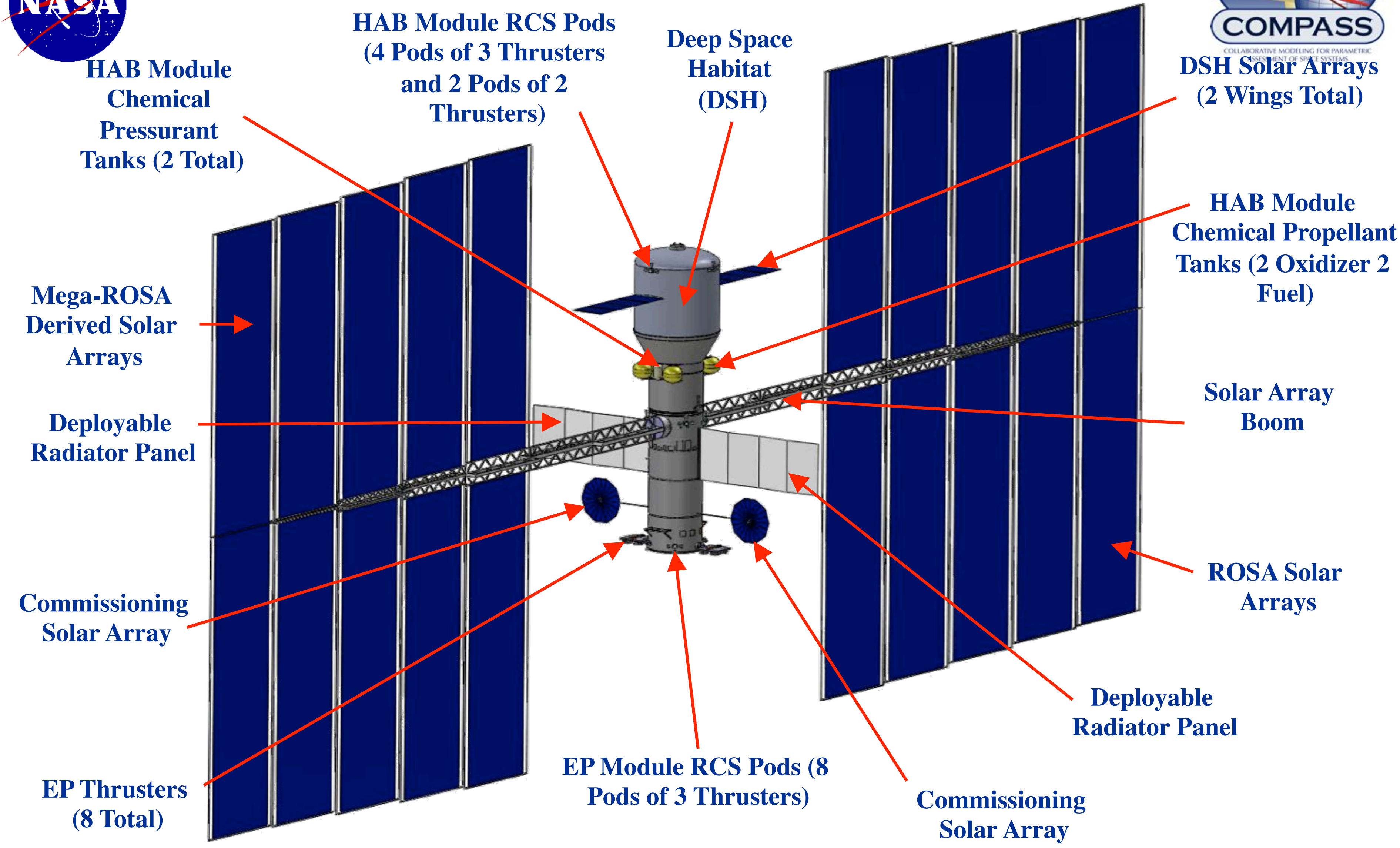


COMPASS Team
NASA John H. Glenn Research Center

12-14-12

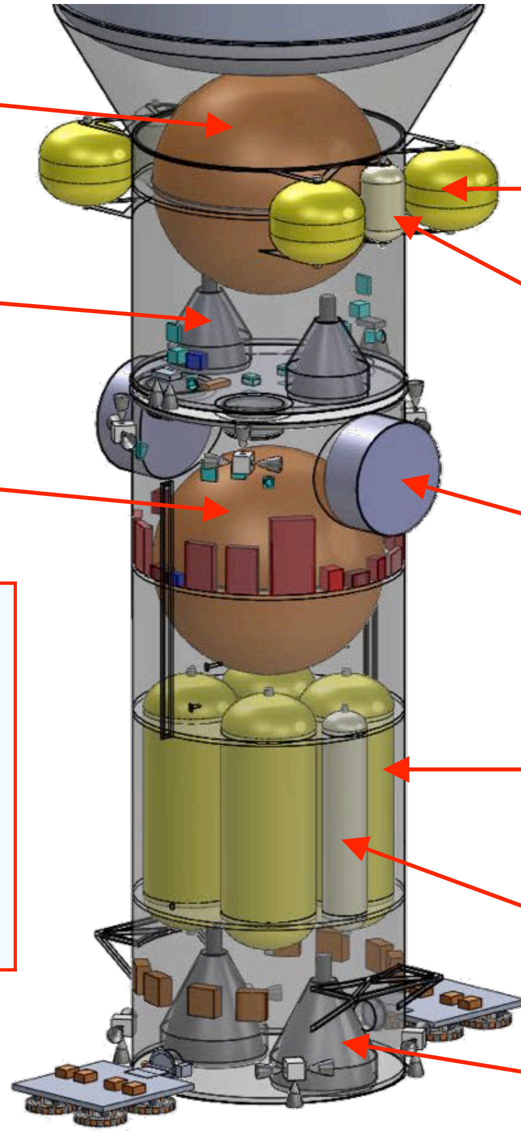
National Aeronautics and Space Administration

Major External Components



National Aeronautics and Space Administration

Internal Bus Components



Subsystems:

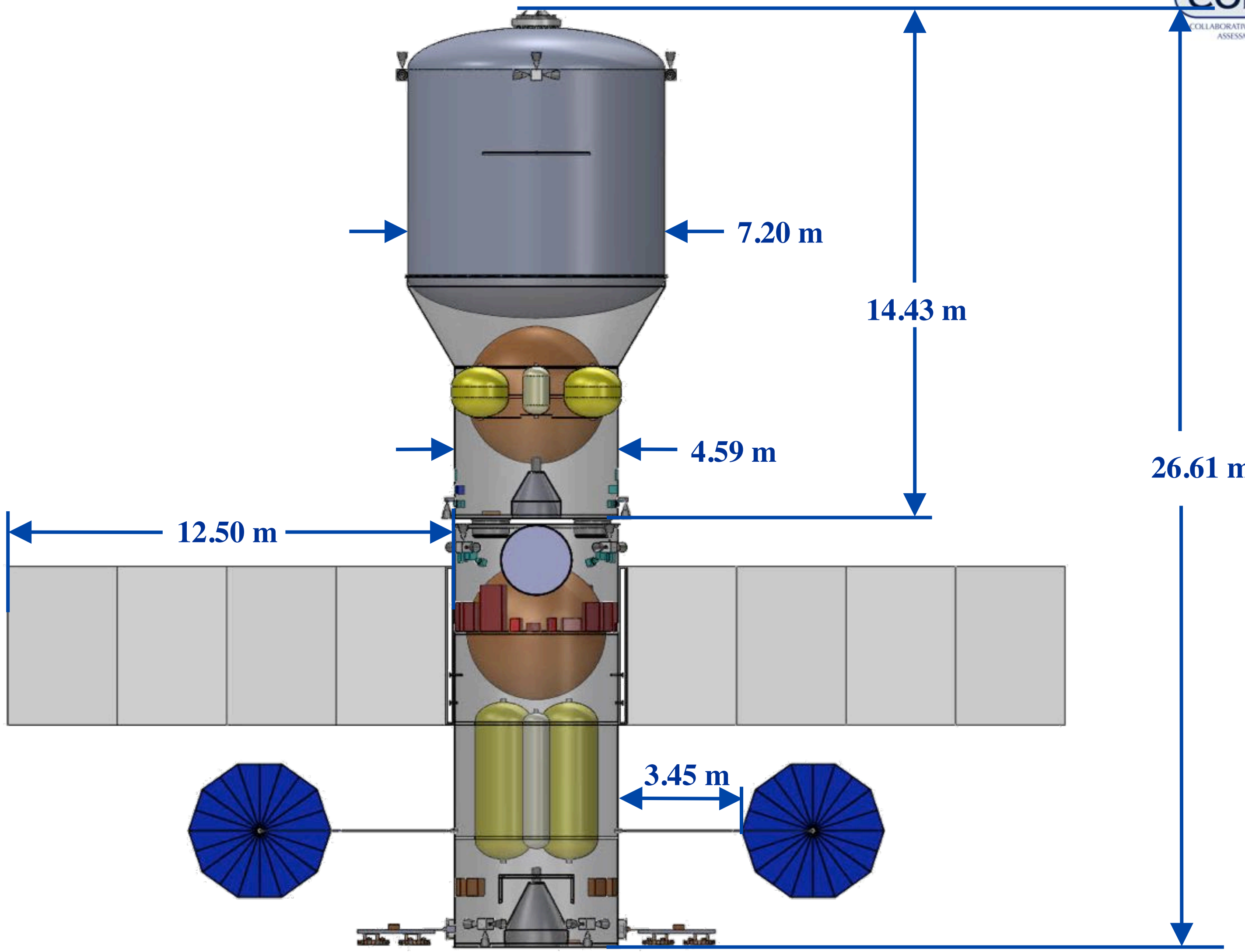
Electrical Power Electronics

EP Feed Systems and DDUs

Command and Data Handling

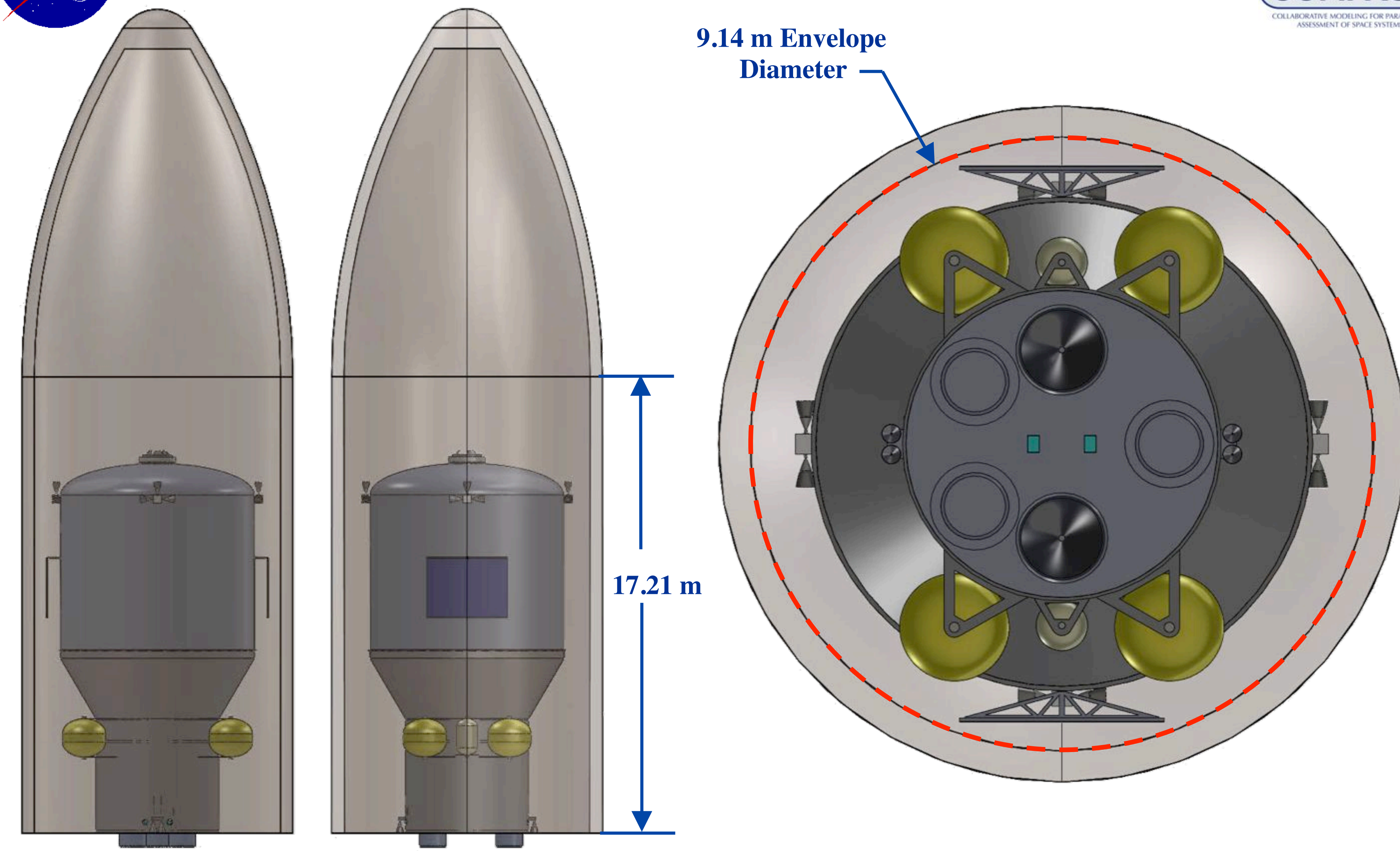
Attitude Determination and Control

Bus Dimensions

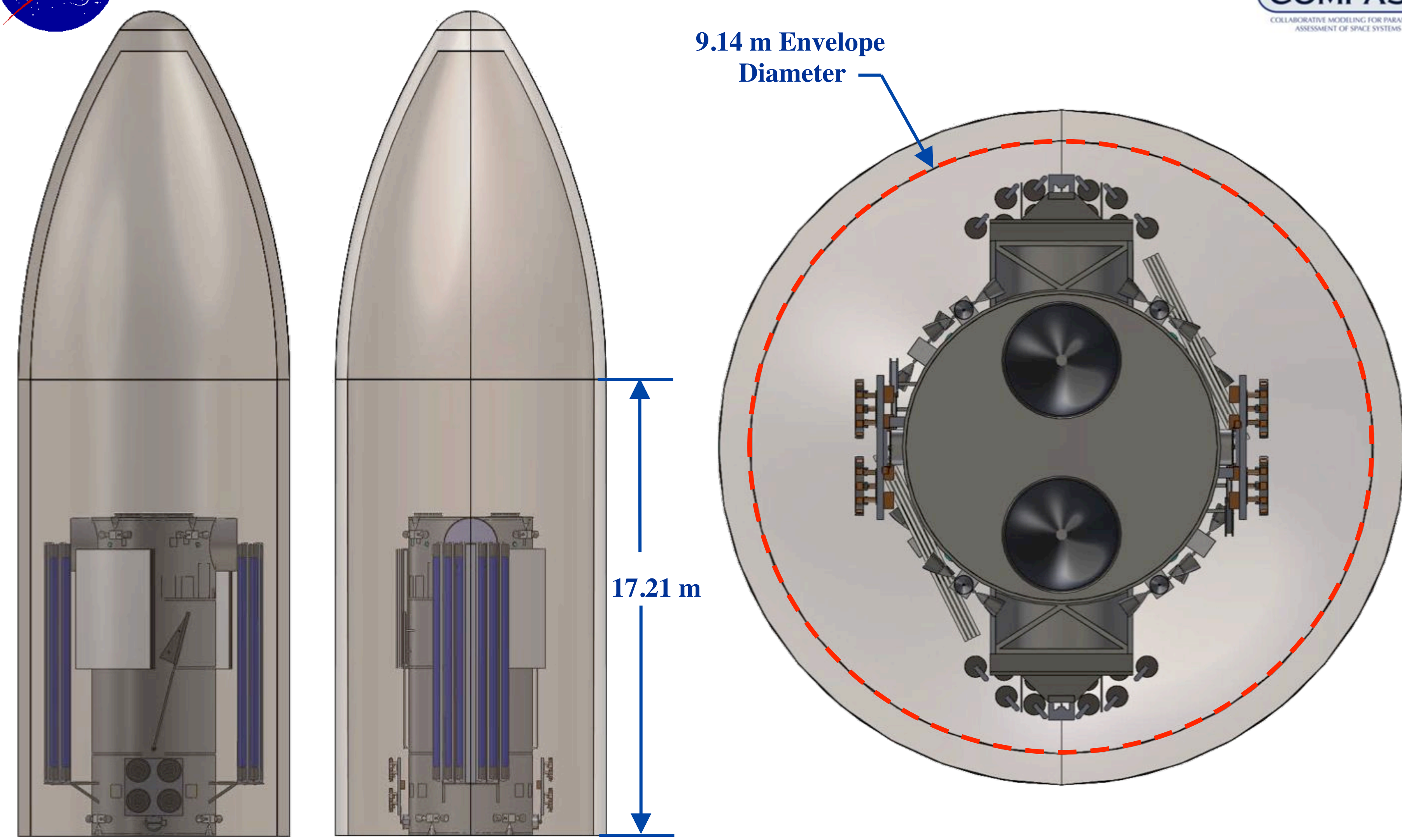


National Aeronautics and Space Administration

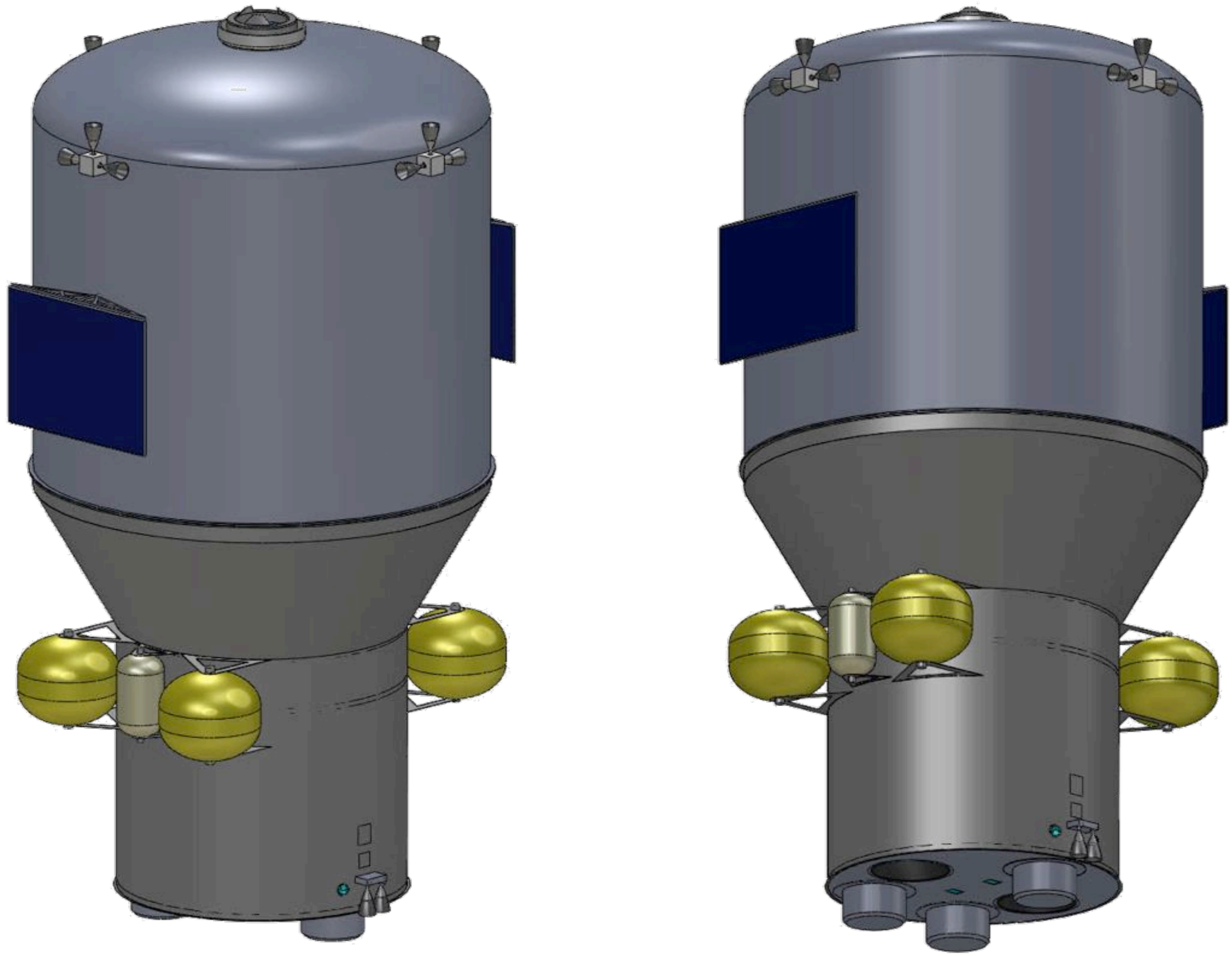
Deep Space Habitat Module Launch Configuration



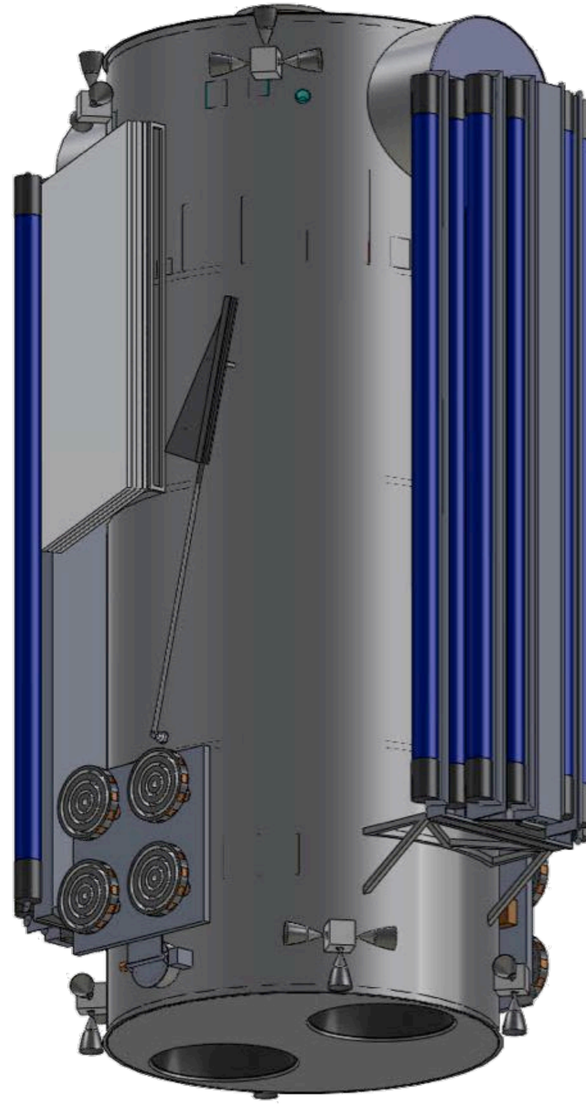
EP Module Launch Configuration



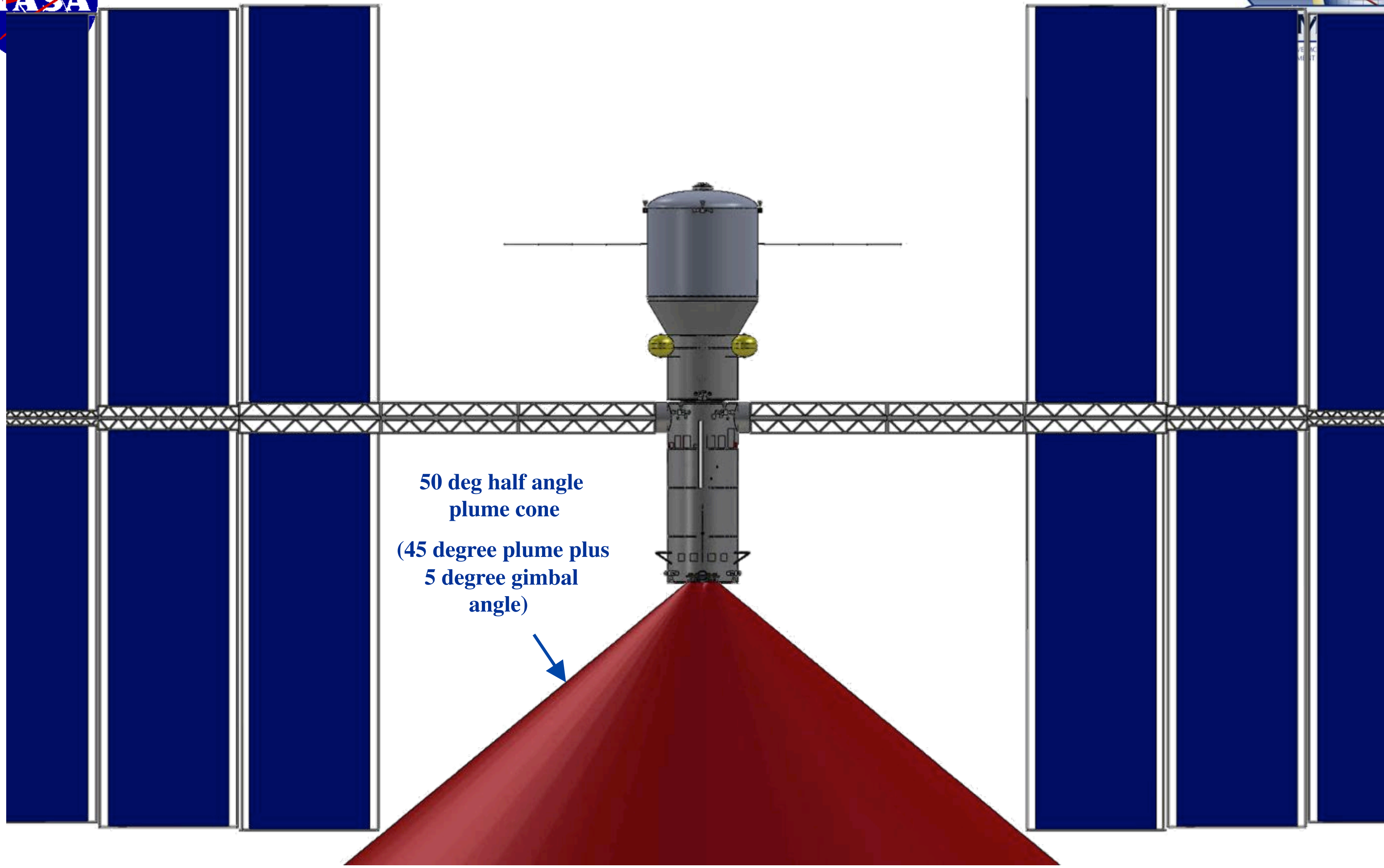
Isomeric Views Of The Stowed Deep Space Habitat Module



Isomeric Views Of The Stowed EP Module

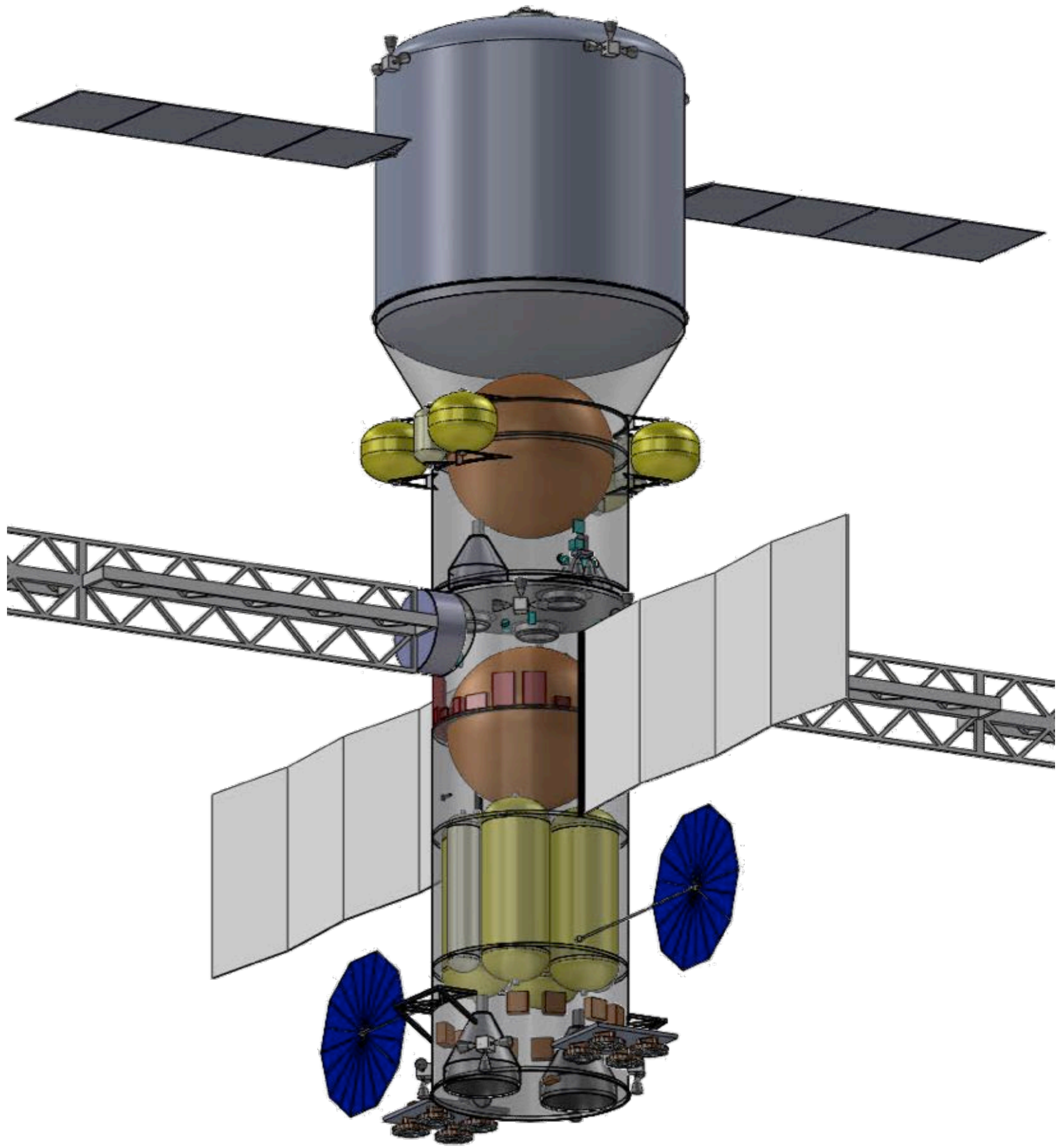


EP Thruster Plume Cone



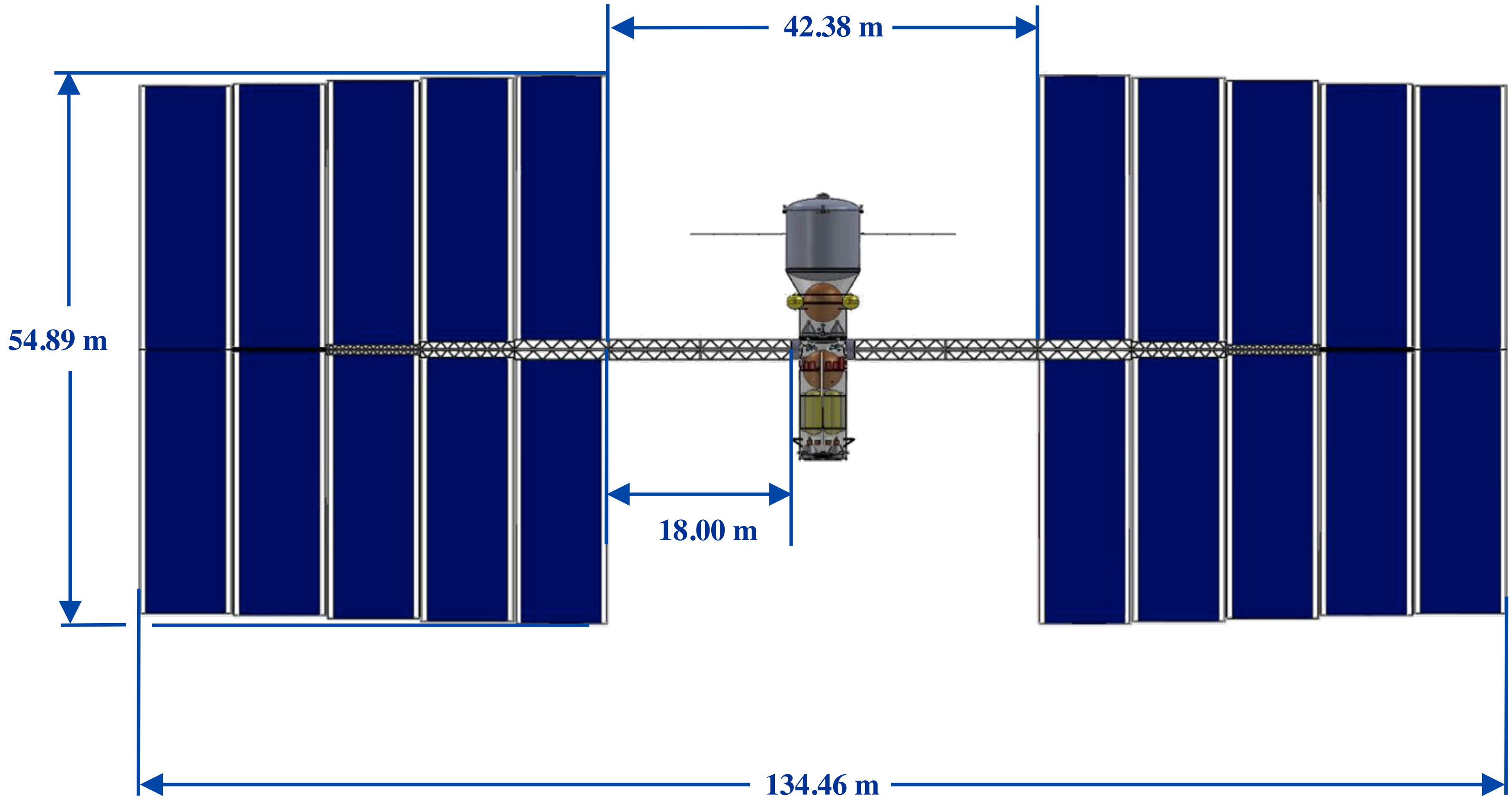
National Aeronautics and Space Administration

Transparent View Of The Mars Piloted SEP Vehicle Bus (1/2)

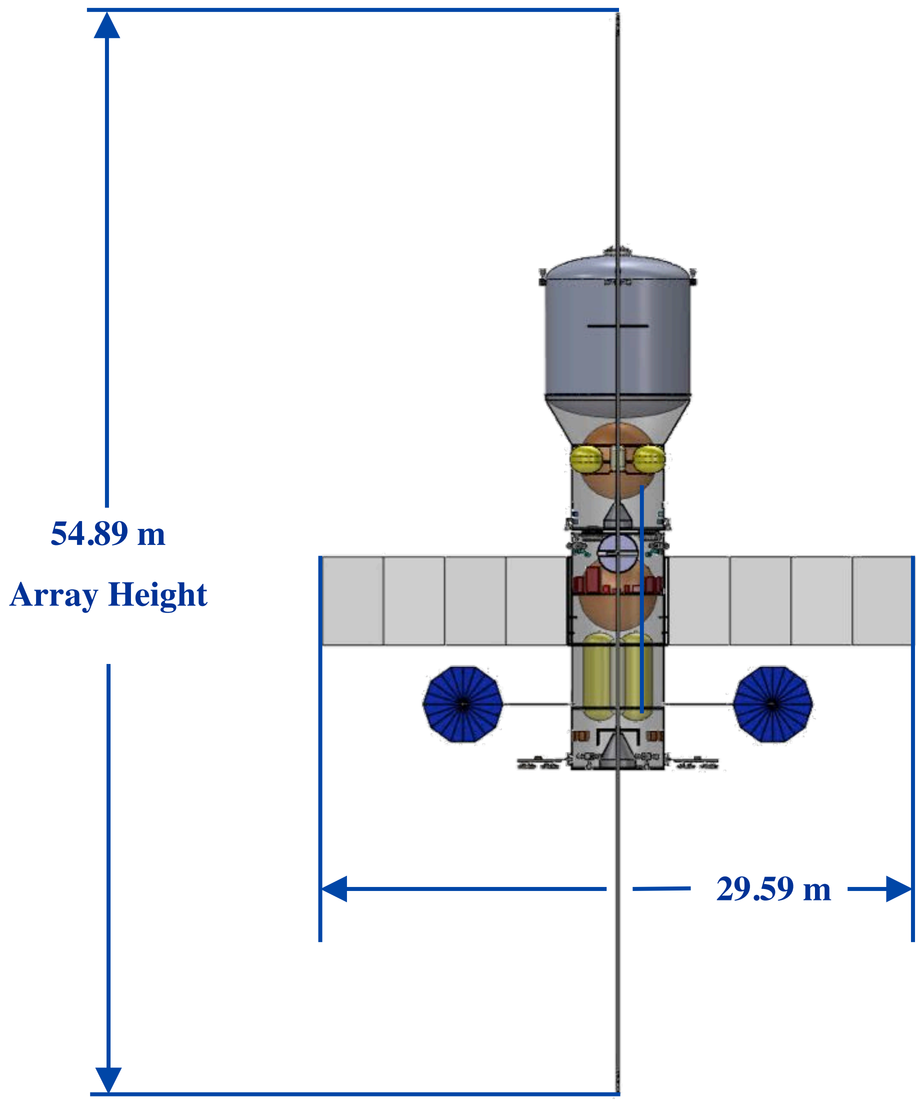


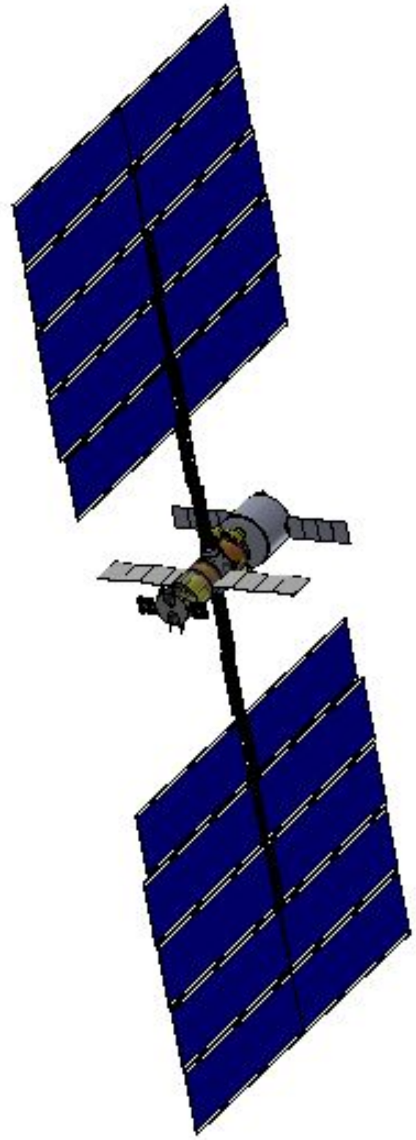
www.nasa.gov

Fully Deployed Dimensions (1/2)



Fully Deployed Dimensions (2/2)





Systems:

Melissa McGuire

COMPASS Team
NASA John H. Glenn Research Center

12-14-12

Mass Growth Allowance (MGA) Schedule

Taken from AIAA S–120–2006, *Standard Mass Properties Control for Space Systems*

Major category	Maturity code	Design maturity (basis for mass determination)	MGA (%) Electrical/electronic components 0 to 5 kg	Electrical/electronic components 5 to 15 kg	Electrical/electronic components >15 kg	Structure	Brackets, clips, hardware	Battery	Solar array	Thermal control	Mechanisms	Propulsion	Wire harness	Instrumentation	ECLSS, crew systems
E	1	**Estimated** (1) An approximation based on rough sketches, parametric analysis, or undefined requirements; (2) A guess based on experience; (3) A value with unknown basis or pedigree	30	25	20	25	30	25	30	25	25	25	55	55	23
E	2	**Layout** (1) A calculation or approximation based on conceptual designs (equivalent to layout drawings); (2) Major modifications to existing hardware	25	20	15	15	20	15	20	20	15	15	30	30	15
C	3	**Prerelease designs** (1) Calculations based on a new design after initial sizing but prior to final structural or thermal analysis; (2) Minor modification of existing hardware	20	15	10	10	15	10	10	15	10	10	25	25	10
C	4	**Released designs** (1) Calculations based on a design after final signoff and release for procurement or production; (2) Very minor modification of existing hardware; (3) Catalog value	10	5	5	5	6	5	5	5	5	5	10	10	6
A	5	**Existing hardware** (1) Actual mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes; (2) Values based on measured masses of qualification hardware	3	3	3	3	3	3	3	2	3	3	5	5	4
A	6	**Actual mass** Measured hardware	No mass growth allowance—Use appropriate measurement uncertainty values												
A	7	**Customer furnished equipment or specification value**	Typically a "not-to-exceed" value is provided; however, contractor has the option to include MGA if justified												

For the COMPASS process, the desired total percentage on dry mass is 30%

Predicted Mass = Basic Mass + Bottoms up MGA%*Basic Mass

Therefore, Additional System level margin = 30% - Bottoms up MGA%

Piloted SEP/Chem MEL Summary

- Balloon Master Equipment list built on the three element standard COMPASS MEL
  - WBS 06.1 Habitat Module
  - WBS 06.2 SEP Module
- MEL contains the Current Best Estimate/Basic Mass, and MGA growth per item to calculate predicted Mass
  - Use COMPASS standard definitions for Masses
- The System summary sheet adds the system level mass to maintain desired growth on basic dry mass per COMPASS design rules

WBS	Description	QTY	Unit Mass	Basic Mass	Growth	Growth	Predicted Mass
Number	Option#3_1 Mars SEP CD-2012-83		(kg)	(kg)	(%)	(kg)	(kg)
	Power Mode Name Power Mode duration (units tbd)						
06	SEP Mars Piloted Vehicle			234058	1.8%	4256	238313
06.1	SEP Piloted SLS Launch 1 - HAB Module			126660	0.7%	848	127508
06.1.1	Habitat			53680	0.0%	0	53680
06.1.2	Attitude Determination and Control			92	3.0%	3	95
06.1.3	Command & Data Handling			47	21.4%	10	57
06.1.4	Communications and Tracking			0	0	0	0
06.1.5	Electrical Power Subsystem			46	50.0%	23	69
06.1.6	Thermal Control (Non-Propellant)			398	18.0%	72	470
06.1.7	Propulsion (Chemical Hardware)			1179	13.2%	155	1334
06.1.8	Propellant (Chemical)			9644	0.0%	0	9644
06.1.9	Propulsion (EP Hardware)			1509	8.4%	127	1636
06.1.10	Propellant (EP)			57359	0.0%	0	57359
06.1.11	Structures and Mechanisms			2706	16.9%	458	3164
06.2	SEP Piloted SLS Launch 2 - SEP Module			107397	3.2%	3408	110805
06.2.1	Misc			0	0	0	0
06.2.2	Attitude Determination and Control			45	3.0%	1	47
06.2.3	Command & Data Handling			121	19.2%	23	144
06.2.4	Communications and Tracking			55	27.8%	15	70
06.2.5	Electrical Power Subsystem			6915	16.1%	1110	8025
06.2.6	Thermal Control (Non-Propellant)			2506	18.0%	451	2957
06.2.7	Propulsion (Chemical Hardware)			2310	16.2%	375	2685
06.2.8	Propellant (Chemical)			34269	0.0%	0	34269
06.2.9	Propulsion (EP Hardware)			3680	11.9%	437	4117
06.2.10	Propellant (EP)			51870	0.0%	0	51870
06.2.11	Structures and Mechanisms			5626	17.7%	994	6620

Piloted SEP/Chem HAB Module System Summary

- Piloted SEP/Chem Case 1 HAB Module: System level growth applied differently per element

Spacecraft MEL Rack-up (Mass) -Option#3_1 Mars SEP CD-2012-83					
WBS	Main Subsystems	Basic Mass (kg)	Growth (kg)	Predicted Mass (kg)	Aggregate Growth (%)
06	SEP Mars Piloted Vehicle	234058	4256	238313	
06.1	SEP Piloted SLS Launch 1 - HAB Module	126660	848	127508	1%
06.1.1	Habitat and systems	53680	0	53680	0%
06.1.2	Attitude Determination and Control	92	3	95	3%
06.1.3	Command and Data Handling	47	10	57	21%
06.1.4	Communications and Tracking	0	0	0	TBD
06.1.5	Electrical Power Subsystem	46	23	69	50%
06.1.6	Thermal Control (Non-Propellant)	398	72	470	18%
06.1.7	Propulsion (Chemical Hardware)	1179	155	1334	13%
06.1.8	Propellant (Chemical)	9644		9644	0%
06.1.9	Propulsion (EP Hardware)	1509	127	1636	8%
06.1.10	Propellant (EP)	57359		57359	0%
06.1.11	Structures and Mechanisms	2706	458	3164	17%
	Element 1 consumables (if used)	13992		13992	
	Estimated Spacecraft Dry Mass (no prop,consum)	45665	848	46513	2%
	Estimated Spacecraft Wet Mass	126660	848	127508	
System LeveL Growth Calculations SEP Piloted SLS Launch 1 - HAB Module					Total Growth
	Dry Mass Desired System Level Growth	5977	1793	7771	30%
	Additional Growth (carried at system level)		946		16%
	Total Wet Mass with Growth	126660	1793	128454	

SEP Piloted SLS Launch 1 - HAB Module: Propellant Details (Chen		
Mass, Propellant Total	9644	kg
Mass, Propellant Useable	8930	kg
Mass, Prop Nav. & Traj. Margin	493	kg
Mass, Prop Residuals	188	kg
Propellant Details (EP)		
Mass, Propellant Total	57359	kg
Mass, Propellant Useable	54399	kg
Mass, Prop Nav. & Traj. Margin	2720	kg
Mass, Prop Residuals	240	kg
Propellant Details (RCS) - From both EP and Chem		
Mass, RCS Total	33	kg
RCS/ACS Used Prop	0	kg
RCS/ACS margin	0	kg
RCS/ACS Residuals	0	kg
RCS/Main/EP Total Loaded Pressurant	33	kg
SEP Piloted SLS Launch 1 - HAB Module Totals		
SEP Piloted SLS Launch 1 - HAB Module Wet Mass	128454	kg
SEP Piloted SLS Launch 1 - HAB Module Dry Mass	47459	kg
SEP Piloted SLS Launch 1 - HAB Module Inert Mass	65125	kg

Architecture Details, SEP Piloted SLS Lau	Mass (kg)	units
Launch Vehicle	SLS	
Delivery Orbit	-92.6 km x 407 km	km2/s2
Gross Payload	123000	kg
ELV Margin (%)	5%	%
ELV performance (post-margin)	116850	kg
ELV Adaptor (2.5 % of SLS gros)	3075	kg
ELV performance (post-adaptor)	113775	kg
Spacecraft Total Wet Mass with System Level Growth	128454	kg
Available ELV Margin	-14679	kg
Available ELV Margin (%)	-13%	%
Targetted IMLEO of HAB Module	113775	kg
ATV Cargo	Mass (kg)	units
Total wet mass of ATV	20,000	kg
Total cargo capability of ATV	8,000	kg
Required Cargo by HAB Module	14679	kg
Excess of ATV cargo capacity	1321	kg
Number of ATVs	2	

- Piloted SEP/Chem Case 3.1 SEP Module: System level growth applied differently per element
- Inert mass calculated for mission, includes dry mass and propellant trapped residuals and margin
- SLS launch vehicle capability to LEO orbit assumed 123,000 kg
- 5% launch performance margin assumed
- Adaptor 2.5% of SLS gross performance (stays with SLS)
- ATV performance assumed 8000 kg
- Number of ATVs calculated by HAB module mass over SLS performance – margin – adaptor.

Piloted SEP/Chem SEP Module System Summary

COMPASS
COLLABORATIVE MODELING FOR PARAMETRIC ASSESSMENT OF SPACE SYSTEMS

06.2	SEP Piloted SLS Launch 2 - SEP Module	*107397*	*3408*	110805	3%
06.2.1	Science	0	0	0	TBD
06.2.2	Attitude Determination and Control	45	1	47	3%
06.2.3	Command and Data Handling	121	23	144	19%
06.2.4	Communications and Tracking	55	15	70	28%
06.2.5	Electrical Power Subsystem	6915	1110	8025	16%
06.2.6	Thermal Control (Non-Propellant)	2506	451	2957	18%
06.2.7	Propulsion (Chemical Hardware)	2310	375	2685	16%
06.2.8	Propellant (Chemical)	34269		34269	0%
06.2.9	Propulsion EP Hardware)	3680	437	4117	12%
06.2.10	Propellant (EP)	51870		51870	0%
06.2.11	Structures and Mechanisms	5626	994	6620	18%
	Element 2 consumables (if used)	0		0	
	Estimated Spacecraft Dry Mass	**21258**	3408	**24666**	**16%**
	Estimated Spacecraft Wet Mass	107397	3408	110805	
System LeveL Growth Calculations SEP Piloted SLS Launch 2 - SEP Module					**Total Growth**
	Dry Mass Desired System Level Growth	21258	6377	**27636**	**30%**
	Additional Growth (carried at system level)		2969		**14%**
	Total Wet Mass with Growth	107397	6377	**113775**	

SEP Piloted SLS Launch 2 - SEP Module: Propellant Details (Chem		
Mass, Propellant Total	**34269**	kg
Mass, Propellant Useable	31747	kg
Mass, Prop Nav. & Traj. Margin	1734	kg
Mass, Prop Residuals	670	kg
Propellant Details (EP)		
Mass, Propellant Total	**51870**	kg
Mass, Propellant Useable	49171	kg
Mass, Prop Nav. & Traj. Margin	2459	kg
Mass, Prop Residuals	240	kg
Propellant Details (RCS) - From both EP and Chem		
Mass, RCS Total	118	kg
RCS/ACS Used Prop	0	kg
RCS/ACS margin	0	kg
RCS/ACS Residuals	0	kg
RCS/Main/EP Total Loaded Pressurant	118	kg
SEP Piloted SLS Launch 2 - SEP Module Totals		
SEP Piloted SLS Launch 2 - SEP Module Wet Mass	**113775**	kg
SEP Piloted SLS Launch 2 - SEP Module Dry Mass	27636	kg
SEP Piloted SLS Launch 2 - SEP Module Inert Mass	**32856**	kg

Architecture Details, SEP Piloted SLS Lau	**Mass (kg)**
Launch Vehicle	SLS
Delivery Orbit	-92.6 km x 407 km
Gross Payload	123000
ELV Margin (%)	5%
ELV performance (post-margin)	116850
ELV Adaptor (2.5 % of SLS gros)	3075
ELV performance (post-adaptor)	113775
Spacecraft Total Wet Mass with System Level Growth	**113775**
Available ELV Margin	**0**
Available ELV Margin (%)	**0%**
Targetted IMLEO of SEP Module	**113775**
ATV Cargo	**Mass (kg)**
Total wet mass of ATV	20,000
Total cargo capability of ATV	8,000
Required Cargo by HAB Module	Not Needed
Excess of ATV cargo capacity	NA
Number of ATVs	NA

- Piloted SEP/Chem Case 3.1 SEP Module: System level growth applied differently per element
- Inert mass calculated for mission, includes dry mass and propellant trapped residuals and margin
- SLS launch vehicle capability to LEO orbit assumed 123,000 kg
- 5% launch performance margin assumed
- Adaptor 2.5% of SLS gross performance (stays with SLS)
- ATV performance assumed 8000 kg
- Number of ATVs calculated by SEP module mass over SLS performance – margin – adaptor.

Piloted Mars SEP-Chem. Lessons Learned

- In general:
- The SEP-Chem. Concept could be considered a ‘Poor-Man’s Nuclear Bimodal’
- Power Limited (<1MW) SEP systems CAN perform piloted Mars missions IF a relatively small storable bipropellant system is integrated: SEP-Chem.
- A very low propellant ‘gear ratio’ of 1 is required – similar to robotic spacecraft (no staging required)
- SEP-Chem. can delivery the crew vehicle to an elliptical 1-sol orbit similar to chemical or NTR systems
- SEP-Chem. *may* have better reliability and abort capabilities due to its dual Propulsion system (14 km/s SEP, 600 m/s storable chemical) and ample power
- Using 800 kW SEP-Chem. can provide 300 day stay-times for 1050d missions
  - Transit Trip times (outbound ~400d, inbound ~300 d) are longer than Chemical or NTR
- SEP-Chem. WILL take >400d to spiral (unmanned) to Gateway to meet the crew
- Belt radiation and ‘weathering’ impacts on
  - Solar array cause a 30% drop in power over mission (accounted for in these designs)
  - Avionics shows that 100 kRad parts
- SLS
  - Planned SLS payloads are about 6t short for the current SEP concept and some consumables or storable propellant (~12t) will need to be delivered using ATV-like vehicles
  - The planned SLS shroud (17 m cylindrical height) is too large for the SEP-Chem. concept payloads – if the shroud is shortened to 10-12m how much would the payload capability increase?

Piloted SEP-Chem.. Lessons Learned #2

- Power/Propulsion
- Two technology options seem to close:
- A 500V solar array coupled with a direct drive 2400s Hall thruster (Baseline Case)
- A 300 V solar array coupled with a high power Hall thruster using a PPU
  - while heavier inertly, provides equivalent performance and more flexibility (due to variable Isp depending on mission phase or abort needs) than the 500V DDU case
- Nested Hall thrusters reduce integration and complexity and provide more continuous thrusting
  - But a single 30-50 kW Hall thruster might be sufficient
- Xenon production for the Piloted (109t) and Two cargo (2 x 74t) missions most probably can be met by properly planning/developing production with current LOX facilities
- Storable Chemical systems provide better performance for the low impulsive ΔV (~600 m/s) SEP-Chem.. mission requirements when compared to cryogenic systems such at LOX/LCH4 due to lighter/denser storage systems

Piloted SEP-Chem. Recommendations

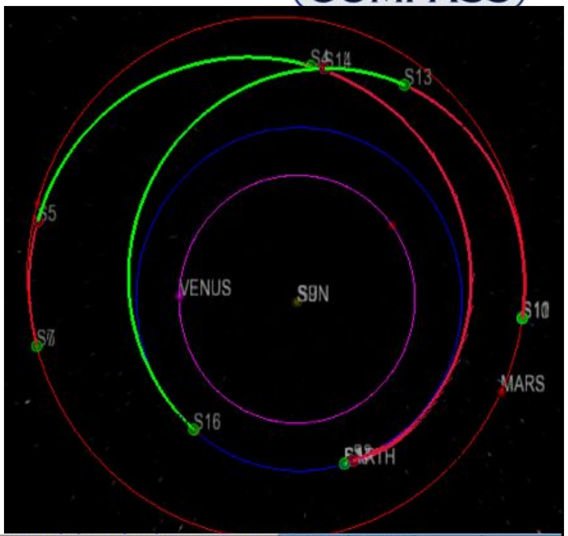
- Run a Case 3.6: Non-Direct Drive, 50 kW Hall, Two Isp Setpoints (2000s and 3000s) to find a possible nearer term solution (Higher TRL).
- Investigate the vibration/harmonics of the large solar arrays due to disturbances (thruster transients, dockings, slew maneuvers)
- Consider adding gyros for the comfort of the astronauts (no continuous ‘bang-bang’ during coasting)

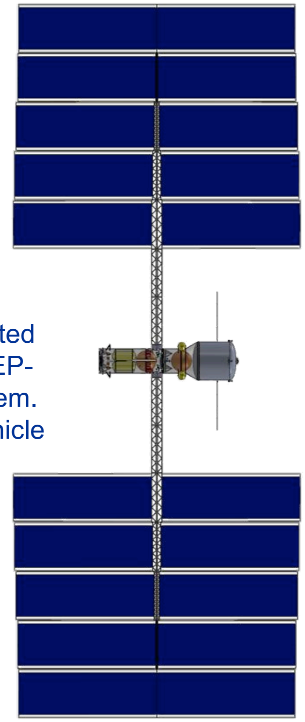
SEP-Chem. Piloted Mars Conjunction Executive Summary

- **Two** SLS launched, 800 kW, 2500s Isp SEP-Chem. Vehicle to deliver 6 crew from EM L2 to elliptical 1 SOL Mars orbit and back to earth duration (includes 300 d stay)
  - Spiral from LEO 400 km to gateway unmanned; MPCV rendezvous
    - **MPCV launch to gateway on separate launcher**
  - Orion Derived Chemical system provides capture/departure from Mars – but 'minimized' by deep Space SEP
  - Total SEP ΔV ~ 14 km/s, Storable Chem ΔV ~700 m/s
- Power:
  - Two 400 kW EOL/1AU Rosa Arrays, 500V regulated from primary solar array, Direct Drive Units (DDUs) to interface between array and Hall thrusters.
  - Common 27m x 8 m roll-out array panels using triple junction IMM cells, arrays boom out to avoid crew vehicles and thrust plumes
- Propulsion
  - Primary SEP: 6+2, 125 KW Hall, Two 3.9 m xenon tanks, ~ 100t xenon propellant
  - Primary Chemical: Orion 7000 lbf storable Bi-prop, 100 lbf thrusters for RSC
- C&DH and Comms
  - Main Computers to operate Module – interface with Hab), 100 GB data storage, L1: multi-Mb/s real-time downlink, NEO: multi-MB/s, Gimbaled HGA for GEO-Mars ops, four medium gain antennas helical for earth ops, X-band
- Thermal
  - Deployed radiators >30,000 Wth from SEP system, MMOD for tanks, Spiral raditation impact <100 krad
- Mechanical
  - Al-Li 5 m thrust tube, composite fittings, 5.5 g launch loads, 0.1g on orbit thrust loads (arrays)
  - Two 400 kW boomed solar arrays, Two thruster gimbal plates +/- 12 °, deployable radiators
- GN&C:
  - Habitat computes trajectory
  - RCS for control, no-roll on SEP spiral, startrackers for pointing knowledge (option for CMGs)


SEP-Chem. Element


Hab Element




Mated SEP-Chem. Vehicle

Main Subsystems	Basic Mass (kg)	Growth (kg)	Predicted Mass (kg)	Aggregate Growth (%)
SEP Mars Piloted Vehicle	234058	4256	238313	
SEP Piloted SLS Launch 1 - HAB Module	126660	848	127508	1%
Habitat and systems	53680	0	53680	0%
Attitude Determination and Control	92	3	95	3%
Command and Data Handling	47	10	57	21%
Communications and Tracking	0	0	0	TBD
Electrical Power Subsystem	46	23	69	50%
Thermal Control (Non-Propellant)	398	72	470	18%
Propulsion (Chemical Hardware)	1179	155	1334	13%
Propellant (Chemical)	9644		9644	0%
Propulsion (EP Hardware)	1509	127	1636	8%
Propellant (EP)	57359		57359	0%
Structures and Mechanisms	2706	458	3164	17%
Element 1 consumables (if used)	13992		13992	
Estimated Spacecraft Dry Mass (no prop,consum)	45665	848	46513	2%
Estimated Spacecraft Wet Mass	126660	848	127508	
L Growth Calculations SEP Piloted SLS Launch 1 - HAB Module				Total Growth
Dry Mass Desired System Level Growth	5977	1793	7771	30%
Additional Growth (carried at system level)		946		16%
Total Wet Mass with Growth	126660	1793	128454	
SEP Piloted SLS Launch 2 - SEP Module	107397	3408	110805	3%
Science	0	0	0	TBD
Attitude Determination and Control	45	1	47	3%
Command and Data Handling	121	23	144	19%
Communications and Tracking	55	15	70	28%
Electrical Power Subsystem	6915	1110	8025	16%
Thermal Control (Non-Propellant)	2506	451	2957	18%
Propulsion (Chemical Hardware)	2310	375	2685	16%
Propellant (Chemical)	34269		34269	0%
Propulsion EP Hardware)	3680	437	4117	12%
Propellant (EP)	51870		51870	0%
Structures and Mechanisms	5626	994	6620	18%
Element 2 consumables (if used)	0		0	
Estimated Spacecraft Dry Mass	21258	3408	24666	16%
Estimated Spacecraft Wet Mass	107397	3408	110805	
L Growth Calculations SEP Piloted SLS Launch 2 - SEP Module				Total Growth
Dry Mass Desired System Level Growth	21258	6377	27636	30%
Additional Growth (carried at system level)		2969		14%
Total Wet Mass with Growth	107397	6377	113775	

SEP Mars Cargo Executive Summary

- 2 SLS Launch
  - 103t Cargo in Aeroshell
  - 113t 800 kW SEP stage from option 3.1
    - BUT offload all but 7t of chemical propellant and add another xenon tank
    - Xenon load now 80t on sep Vehicle - no xenon on cargo
- Meet up in LEO
- Spiral to escape (~400 days)
- Thrust to Mars but separate SEP before capture
  - Option for SEP to flyby Mars and return to Gateway
- Cargo vehicle captures using aerocapture system